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overview and development of disregarded models

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Steady-state cosmologies: overview and development of disregarded models

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Steady-state cosmologies: overview and development of disregarded models

by Eve-Aline Dubois

Abstract: The current cosmological paradigm is the Hot Big Bang with the addition of dark matter and dark energy. This theory has evolved during the whole last century to become the most acceptable one. History has the tendency to forget. Indeed, several cosmological models have been abandoned and forgotten. The purpose of the present work is to recount the development of another family of cosmologies. The aim is to expound the diversity of the steady-state cosmologies and the evolution of the most famous of them, the Steady-State Theory. The chronological approach permits to show the different motivations leading to these models, their various interpretations and their unexpected progression.

Cosmologies stables : panorama et développement de ces modèles méconnus

par Eve-Aline Dubois

Résumé : Le *Big Bang* chaud, augmenté de matière noire et d'énergie sombre, est aujourd'hui le paradigme de la cosmologie. Cette théorie s'est construite tout au long du siècle dernier jusqu'à devenir la plus acceptée. Cependant, l'histoire a une certaine tendance à l'oubli. En effet, plusieurs modèles cosmologiques ont été abandonnés puis oubliés. L'objectif du présent travail est de retracer le développement d'une autre famille de cosmologies. Le but est de présenter la diversité des modèles stables et l'évolution du plus célèbre d'entre eux, la *steady-state theory*. L'approche chronologique adoptée permet de montrer les différentes motivations menant à ces modèles, leurs interprétations variées et leur progression inattendue. Si ces modèles ne sont pas retenus aujourd'hui il n'empêche que leurs idées originales ont leur place dans le formalisme actuel.

Ph.D. thesis in Mathematics
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naXys Research Institute and Esphin
Department of Mathematics
Advisors: André Fűzfa and Dominique Lambert

We believe that the world behaves according to certain inviolable rules and that, by persistent effort, we can discover those rules and use them to predict events when circumstances repeat.

CHRISTOPHER PAOLINI
The Inheritence cycle II: Eldest

A ma grand-mère.

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My friend, this song's for you,
you're such a good man and you really ought to know that when we're apart,
I think of you, Ok maybe not everyday, but still I do.

My Friend -Babylon Circus-

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cette thèse, la boucle est bouclée, merci pour cet encadrement.
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Eve-Aline
Namur, juillet 2021

Contents

Introduction

Il n'y a pas de coïncidences, l'usage de ce mot est l'apanage des ignorants

Moon Palace -Paul Auster-

Any coincidence is always worth noticing.
You can throw it away late if it is only a coincidence.

Nemesis -Miss Marple-

Before jumping into the science and the history of cosmology, we shall take the time to think about a crucial concept for the present work: the idea of coincidence.

First of all, we shall try and answer: what is a coincidence? Looking into a dictionary, a coincidence is no more than some events occurring at the same time. The coincidence contains an idea of simultaneity. In the everyday language, there is an additional notion in the use of this concept. Something is bothering in coincidences. The simultaneity is questioned because it links two, or more, facts that seem to be independent. By reference to Jacques Monod's well-known book, coincidence is interrogating the fundamental antagonism between chance and necessity. Generally, this vocable is used in a negative sentence: "this could not be a coincidence". The coincidence troubles.

In science, in particular, coincidences are not well accepted. We try to explain them. We try to make connexions and to turn a coincidence into an explained causal relationship. It could not be a coincidence if every time I drop my eraser, it ends its journey on the floor. It could not be a coincidence if every time I press a specific button, the light turns on in the room. In those examples, as the simultaneity is noticed every time, calling it a coincidence would be bothering, but it could be even more frustrating.

Is it a coincidence, if the universe has just the minimum number of dimensions that makes our life possible? Is it a coincidence, if when we look up to the sky above us, there is no evidence of privileged direction?

The scientific answer to the second question is to build up a principle stating that the universe is homogeneous and isotropic. This approximation permits to work with mathematical tools to describe the observed universe. The first question raises complicated and diversified answers. With the number of dimensions, there are other specific values which seem to need a very precise adjustment to let us live. Some say that these numbers are fine-tuned, and therefore requiring a fine-tuner. Others try to conceive physical mechanisms leading a large panel of initial conditions to the precise measured values. You can imagine other solutions to those questions, but you cannot deny that there is a question. Coincidences are hard to admit and a scientist will try to explain them at any cost.

In the present work, we have the ambition to present some little-known cosmological models. Most of them failed to explain all the emerging observations or to stand up the current hot Big Bang theory. If, sometimes, an exposed idea seems to be disturbing or does not fit in your way to see the world; just remember how you feel in front of a coincidence and, please, appreciate the effort to explain it, even if the expounded reasoning would not be yours.

The present book is divided into three parts. In the first one, two chapters lead the reader from the first myths of creation to modern cosmology, by discussing the epistemological status of cosmogony and cosmology. The second part presents a series of steady-state cosmologies of the first half of the twentieth century. It goes from Einstein's unknown draft to the famous Steady-State Theory of Hoyle passing by the Dirac principle and Jordan's works. The third and last part of this book studies the attempt from Hoyle and his colleagues to save the Steady-State Theory regarding the observational data of modern cosmology, such as the Cosmological Microwave Background. Finally, this thesis will be concluded by a summary of the accomplished work and some perspectives to express the contribution and the influence of steady-state cosmologies over modern cosmology. In the appendix, can be found different translations from German that were needed for this research and the published contributions of the author.

To facilitate the reading, the layout of this book has been thought to be reader-friendly. Each chapter begins with a description of its content in two or three points. Moreover, the text is peppered with some insets. The reader has the choice to read them or not, without imperilling his understanding. There are different kinds of frames, depending on their subject: a portrait, a technical development, or a quotation.

This thesis has been written based on numerous reading. The author has attempted to quote, as much as possible, the primary sources. Unfortunately, after the reading of so much important and interesting secondary literature, the quotation process turned out to be more difficult. It was easy to locate the original source of a result or an idea. It was difficult to do the same for more global analysis built on the accretion of readings, knowledge and ideas. The author would like to apologize for paying less tribute to secondary literature at the benefit of primary ones. She can only thank these many sources of inspiration duly cited in the bibliography at the end of this work. For those who want to enter into the field of the history of cosmology, she can recommend Helge Kragh's works and the biographies.

Contributions

- E.-A. Dubois, A. Füzfa, *On the diversity of stationary cosmologies in the first half of the twentieth century*, General Relativity and Gravitation 51:1, 2019
https://doi.org/10.1007/s10714-018-2496-8 ;
- E.-A. Dubois, A. Füzfa, *Comments on P. Jordan's Cosmological Model*, Universe 6:82, 2020
https://doi.org/10.3390/universe6060082 ;
- E.-A. Dubois, *1937: Année de l'hypothèse des grands nombres*, Revue des questions scientifiques 192, 2021.

Notation

	Acronym	Meaning
Abbreviations	AGN	Active Galaxy Nucleus
	BBN	Big Bang Nucleosynthesis
	CMB	Cosmological Microwave Background
	GR	General Relativity
	ISM	InterStellar Medium
	LNh	Large Numbers hypothesis
	PCP	Perfect Cosmological Principle
	QSO	Quasi-Stellar Object
	QSST	Quasi-Steady State Theory
	SST	Steady-State Theory
	WCP	Wide Cosmological Principle

	Symbol	Meaning
Constants	A	Age of the universe
	α	fine-structure constant
	c	Speed of light
	e	Charge of the electron
	ϵ_0	Vacuum permittivity
	G	Gravitational Newtonian constant
	γ	Epoch
	h	Planck's constant ($\hbar = \frac{h}{2\pi}$)
	H	Hubble's constant
	k	Curvature of the hyper-surface
	k_c	Coulomb's constant
	κ	Einstein's constant ($\frac{8\pi G}{c^4}$)
	λ	Cosmological constant
	m_e	Mass of the electron
	m_p	Mass of the proton
	μ	Average mass of the universe
	μ_0	Magnetic vacuum permeability
	ν	Frequency
	p	Hydrostatic pressure of the universe
	ρ	Average density of matter of the universe

	Author	Notation	Convention in this thesis
Conventions	Bondi and Gold	α	Scale factor $a(t)$
	PAM Dirac	$f(t)$	Scale factor $a(t)$
	PAM Dirac	m	Mass of the electron m_e
	PAM Dirac	M	Mass of the proton m_p
	P. Jordan	α	Hubble's constant H
	P. Jordan	f	Gravitational constant G
	P. Jordan	Λ	Atomic length unit
	P. Jordan	μ	Average density of the universe ρ
	F. Hoyle	$G_{\mu\nu}$	Ricci tensor $R_{\mu\nu}$
	F. Hoyle	G	Scalar curvature R
	F. Hoyle	R	Scalar factor $a(t)$
	F. Hoyle	$\mu = 1 : 4$	Coordinates $\mu = 0 : 3$
	F. Hoyle	$S(t)$	Scale factor $a(t)$

	Notation	Meaning
Formalism	$a(t)$	Scale Factor
	$C_{\mu\nu}$	Creation tensor
	$\dot{}$	Time derivative
	ds^2	Line element
	$g_{\mu\nu}$	Metric tensor
	$G_{\mu\nu}$	Einstein's tensor
	R	Scalar curvature
	$R_{\mu\nu}$	Ricci tensor
	R_s	Schwarzschild radius
	S	flux density
	Greek subscripts	Four dimensions
	Latin subscripts	Three dimensions
	$T_{\mu\nu}$	Stress-energy tensor
	u_μ	4-velocity vector
	Ξ	Compactness
	z	Redshift

Part I

Contextual Settings

Chapter 1

From cosmogony to modern cosmology

Nulla unquam inter fidem et rationem vera dissensio esse potest

Dei Filius -First Vatican Council-

In this chapter:

- A definition of cosmology, in opposition to cosmogony
- A presentation of the precursors of modern cosmology
- A enunciation of disrupting observations

1.1 What is cosmology?

We shall be careful and define one of the most frequent words of this thesis: cosmology. This notion must be distinguished from cosmogony. Our first reflex shall be to consult a dictionary.

The distinction between those two terms is not so clear. The difference is usually made on the validity domain of the word. Cosmology belongs to science when cosmogony is more of a mythical, religious or philosophical model of the universe. In most cases, cosmogonies are a way to include humanity in a larger structure and to situate the human beings in their world. This is not this concern in the field of cosmology.

Cosmogony the study of the origin and development of the universe or of a particular system in the universe; a theory of such an origin or evolution.
Cosmology theory about the origin and nature of the universe.

-Collins-

Even with this clarification, or with the definitions in the above sidebar, the distinction is not so clearly defined. Perhaps some examples could illustrate the distinction and the porous frontier between those two concepts.

Ancient Egyptian myths are wonderful examples of cosmogony, as illustrated in the next box. They are a possible explanation of the origin of the universe, made without any recourse to science. The tale is based on the existence of some divinities, themselves completely disconnected from scientific explanation.

Memphite myth of creation

It is written that at the beginning of time, Ptah the demiurgus, who is from Noun, the primordial ocean, became aware of its existence. Then he took the silt of the earth, creating and shaping Man. As soon as his creative work was finished, he gave way to his successor Ra, the sun. Ra, lord of Heliopolis, travels each day its domain providing humanity with gifts and benefits[a]*.*

[a] Bickel 1994.

Plato, in *Timaeus*, suggests what is, according to him, a rational explanation of the formation of the universe, cf. box below. The demiurge modelled the matter of the universe in one long slab. He divided it, along length. In one half was the *Same*, what remains exactly itself; in the second half was the *Other*, what changes through time. The demiurge bound these two parts in huge circles and produced a sphere by rotating them around the same center.

The *Same* was responsible for the motion of what remains similar to itself, such as the celestial sky and the stars. The *Other* was responsible for the motion of what changes, such as the interior of the cosmos.

Next, He split all this that He had put together into two parts lengthwise; and then He laid the twain one against the other, the middle of one to the middle of the other, like a great cross; and bent either of them into a circle, and join them, each to itself and also to the other, at a point opposite to where they had first been laid together. And He compassed them about with the motion that revolves in the same spot continually, and He made the one circle outer and the other inner. And the outer motion He ordained to be the Motion of the Same, and the inner motion the Motion of the Other. And He made the Motion of the Same to be toward the right along the side, and the Motion of the Other to be toward the left along the diagonal; and He gave the sovranty to the Revolution of the Same and of the Uniform. For this alone He suffered to remain uncloven, whereas He split the inner Revolution in six places into seven unequal circles, according to each of the intervals of the double and triple intervals, three double and three triple. These two circles then He appointed to go in contrary directions; and of the seven circles into which He split the inner circle, He appointed three to revolve at an equal speed, the other four to go at speeds equal neither with each other nor with the speed of the aforesaid three, yet moving at speeds the ratios of which one to another are those of natural integers[a]*.*

[a] *Timaeus*, 36b-36d.

This explanation of the creation of the universe is a myth, requiring a demiurge. However, it is also an attempt to explain the constitution of the universe, with what has a regular motion and seems eternal and what has an irregular motion and seems to evolve [1].

The border between science and myth is not always very clear and the definitive transition from cosmogony to cosmology takes a lot of time and the participation of many great minds.

[1] The retrograde motion of Mars was already known by the Ancient Greeks.

It is important to note that as cosmologies try to explain the world, they explain its creation, with the underlying idea of a beginning. A notable exception is the Hindu cosmology based on a perpetual cycle of creation and destruction. In this conception, there is no clear beginning of the series of cycles. The philosophy also could be coined as an attempt to think of an eternal universe, backwards and forwards. For Neoplatonism, the world is perpetual because it has no cause. In Plotinus' view, the universe is time-infinite as its cause is eternal and unchanging[2]. Most of the cosmologies rest upon creation, a universe with a finite past. Yet the question of the infinity of the future is more debatable.

1.2 The Early stages

In this section, some characters who did a lot to emancipate the cosmology from the cosmogony are presented. The first one that the author wants to quote as a founder of modern cosmology is Nicolaus Copernicus, followed by Johannes Kepler. The third and last one is Isaac Newton. Of course, the list is not at all exhaustive and conveys the clear position pro-Renaissance of the author. Ulugh Beg, Tycho Brahe, and Galileo Galilei are some examples of famous astronomers forgotten on purpose and in full knowledge of their important influence on astronomy.

After that, some precursor cosmological models are introduced: Pierre Simon de Laplace's and Henri Poincaré's. Those two theories are forerunners of modern cosmology as they did not have the general relativity as a basement.

A lot has been written about N. Copernicus (1473-1543) and it is difficult to separate the good from the bad. One thing is certain: Copernicus has written *De Revolutionibus orbium coelestium* for several years, meanwhile sharing his ideas with some friends and people he trusted. Copernicus finally decides to diffuse his manuscript when approaching death.

De Revolutionibus consists of an approximation of a mathematical model of the universe. The principal idea is that the calculations and the astronomical previsions would be more accurate and easier if the astronomers considered that the Earth and the planets orbit around the Sun, and not the opposite, the Sun and the planets around the Earth. This model, called heliocentric, is in clear contradiction with the paradigm of the Ptolemaic system of spheres modelling the world as geocentric.

[2]Van Steenberghen 1978.

Copernicus' main text clearly states that heliocentrism is not just a calculation artefact but is the right representation of the universe; the preface, written by the theologian Andreas Osiander, is not so definitive. Osiander presents Copernicus' model as a help for the astronomers, as a mathematical trick, but not as a representation of the world as it is. This precaution means that either Osiander did not understand Copernicus' work and truly believed it is just a knack; or, he did understand Copernicus and measured the risk to defend the heliocentric model. Indeed, the Catholic position was in accordance with the *Bible* and Aristotelian model: the Earth is the center of the world, the Sun and the planets revolve around it. In the middle of the sixteenth century, the Vatican and the religious power are strong enough to forbid the heliocentric model. With the precautions made in the preface, *De Revolutionibus* could be printed and circulate through Europe.

Some years later, it seems evident that Giordano Bruno has carefully read Copernicus' masterpiece. Indeed, in some of Bruno's texts, the references to Copernicus and the heliocentric model are crystal clear[3]. Apparently, it is at the beginning of the seventeenth century, after Bruno's conviction and during Galileo's trial, that the subversive message of *De Revolutionibus* has been measured by the Church. Copernicus' book has been forbidden in 1616, seventy-three years after its first publication.

With *De Revolutionibus*, Copernicus, although he is a clergyman[4], is one of the first to defend a cosmological position against religion. This work permits to diffuse a scientific model with no regard to its contradictions with the religious paradigm. Surely, other men did that before Copernicus, but it is the first example of a largely known work on the heliocentric conception of the universe.

Johannes Kepler (1571-1630) is known for his works *Astronomia nova* and *Harmonices Mundi*. In those books, Kepler explores, among other things, the heliocentric universe as introduced by Copernicus. Doing so, he suggests his model built on the basis of a huge quantity of observations and with mathematical tools.

Kepler's laws are famous and are always taught today. The first one states that the orbits followed by the planets, including Earth, around the Sun, are elliptic when they were circular in Copernicus' model. The second and the third ones are less popular. Kepler states that the areas swept by a radius

[3]For example, Bruno's *La cena de le ceneri* (The Ash Wednesday Supper) is a splendid defence of Copernicus' model.

[4]Educated and protected by his uncle, bishop of Warmia, Copernicus was a canon himself.

vector from the Sun to the planet are equal for equal sets of time. This second law presages the conservation of the angular momentum. Then, Kepler links the orbital period of the planetary motion around the Sun and the major axis of the elliptical orbit. The cube of the period is proportional to the square of the semi-major axis.

These two last laws mean a lot for the evolution of cosmology. With them, astronomy is now written in a mathematical language and not only described by complicated constructions based on intuition. Johannes Kepler opens the door to the mathematization of astronomy. He also has a feeling that there is a distant force, prefiguring gravity.

Isaac Newton (1643-1727) is an historical character surrounded by myths and legends. The important point that leads him to be quoted in this chapter is his universal law of gravitation, published in *Philosophiae Naturalis Principia Mathematica*.

This gravitational law is revolutionary. The same scientific description applies as well to the falling apple as to the motion of the Moon around the Earth. The Aristotelian conception of two different worlds, and so two different kinds of explanations for the sublunary space and the celestial sphere, is ruled out. The universe is a whole, following everywhere the same rules. With this idea, scientific exploration explodes. Scientists can explain the terrestrial world but also the celestial one. Space is no longer a home for angels and gods but becomes the playground for physicists and astronomers.

With Isaac Newton, the umbilical rope bounding the cosmology to the cosmogony is definitely cut. Physicists can interrogate the whole universe with mathematical tools without depending on religious aspects. It is quite ironic that Newton, clergyman himself and very convinced of the literal meaning of the *Bible*[5], is the one to finalize this separation.

To illustrate this separation between cosmological science and religion, the example of Pierre Simon de Laplace (1749-1827) is representative.

In 1847, Victor Hugo shares an anecdote that François Arago was pleased to tell. In this little story, repeated in the box below, Laplace states that science does not need God nor a divine motor to function.

[5]The literal reading of the verses Joshua 10:12 is usually used as a divine reference for the geocentric model.

M. Arago avait une anecdote favorite. Quand Laplace eut publié sa Mécanique céleste, disait-il, l'empereur le fit venir. L'empereur était furieux.
- Comment, s'écria-t-il en apercevant Laplace, vous faites tout le système du monde, vous donnez les lois de toute la création, et dans tout votre livre vous ne parlez pas une seule fois de l'existence de Dieu !
- Sire, répondit Laplace, je n'avais pas besoin de cette hypothèse.[a,b]

[a] Hugo 1913, p.271.

[b] Mr.Arago had a favorite anecdote. When Laplace had published his *Mecanique céleste*, he told, the emperor sent for him. The emperor was furious.
- Pardon, he exlaimed noticing Laplace, you make the whole system of the world, you give laws of all creation, and in your whole book you don't mention once the existence of God!
- Lord, replied Laplace, I had no need for this hypothesis.

In his *Traité de Mécanique Céleste*, Laplace transforms the geometrical approach, suggested by Newton, into an approach based on mathematical analysis. Doing so, Laplace contributes to the emergence of mathematical astronomy. Definitely, cosmology, as the science of the whole universe, is now independent of God.

Henri Poincaré (1854-1912) is a famous physicist and mathematician. He could be viewed as the first to present relativity in a modern context. He is evoked in this chapter because of his work in *Leçons sur les hypothèses cosmogoniques*. Strangely enough, Poincaré's title refers to cosmogony and not to cosmology.

He has this powerful overview of the scientific challenges of the early twentieth century. He has the presentiment that for becoming a full-blown science, cosmogony has to lay on more experiments and observational data, as evidenced by the extract in the following insert. By doing so, according to Poincaré, cosmogony will finally evolve to become a science, now called cosmology.

La cosmogonie va-t-elle donc sortir de l'âge des hypothèses et de l'imagination pour devenir une science expérimentale, ou tout au moins une science d'observation ?[a,b]

[a]Poincaré 1911, p.XVII.

[b]Will cosmogony thus emerge from the age of hypotheses and imagination to become an experimental science, or at least an observational science?

1.3 The Metamorphoses

The upheavals required by Poincaré to transform the cosmogony into a science of experiments or of observations occur the following decade. These changes are the general relativistic theory developed by Einstein, the identification of the spiral nebulae as galaxies, and the observation of the recession of these galaxies.

After special relativity published in 1905, Albert Einstein published, in 1915, his general relativistic theory[6].

With this theory, Einstein links special relativity and gravitation. Doing so, he can explain one of the weaknesses of the Newtonian theory: the shift of Mercury perihelion. General relativity is the perfect physical theory, tooled with the appropriate mathematical formalism, to described space-time. In this conception, the gravitation is not an instantaneous interaction but a deformation of space-time itself.

In the same way that Newtonian gravitational theory can be extended from terrestrial phenomena to the solar system; general relativity can be applied to the whole universe.

Till the 1920s, the universe is reduced to our own galaxy, the Milky Way. The nebulae are clouds of stellar gazes belonging to our galaxy. Some authors, like Kant, postulate the model of island-universes. This enlarges the cosmos but restrains the concept of universe to one galaxy at the time.

[6]Einstein 1915.

The *Great Debate* opposes the two positions, the 26th April of 1920[a]. On the one hand, Harlow Shapley defends the idea of a universe equivalent to the Milky Way. In some publications[b], he explains why the nebulae must be included in our galaxy. On the other hand, Heber Curtis supports the idea of extra-galactic nebulae[c]. For this, he relies on Slipher's observations of shifts of nebulae[d]. At this time, they observe both blue and red shifts and recognise in them a Doppler effect. At the end of 1924, Hubble closes the debate with his measurements of spiral nebulae distance with the help of the cepheid method[e,f]. Spiral nebulae are large and distant, and galaxies similar to our Milky Way.

[a] Shapley and Curtis 1921.
[b] Shapley 1919.
[c] Curtis 1917.
[d] Slipher 1913.
[e] Times 1924.
[f] Hubble 1925.

With the technical ameliorations of optical instruments, the resolution of spiral nebulae pictures improves. It can be shown those nebulae are nothing more than galaxies, as our own. This was not easily accepted as evidenced by the *Great Debate* explained above. The universe grows in one discovery. It is not limited to the Milky Way but it includes a plethora of galaxies. With this observation, the universe is bigger than ever and the investigation field for physicists seems gigantic, if not infinite.

In the second part of this specific decade, the universe enlarges again. From observations, it seems that not only are nebulae galaxies but they also have their own motion. The galaxies are fleeing away, the further the faster (for more information see the box below).

In 1929, Hubble publishes a famous relation between distance and radial velocity among extra-galactic nebulae[a]. He establishes a roughly linear relation between velocities and distances. However, Hubble does not link this result with a potential dynamics of the universe. This relation echoes the dynamical universe suggested by G. Lemaître[b].

[a] Hubble 1929.
[b] Lemaître 1927.

This observation has two consequences. The universe is large and becomes larger and larger. Moreover, if we look back in the past, the universe is smaller and smaller. The universe is huge and dynamical.

Chapter 2

First steps of cosmology

Il fallait être Newton pour prévoir que la Lune tombe,
alors que tout le monde voit bien qu'elle ne tombe pas.

Mélange -Paul Valery-

In this chapter:

- An introduction to cosmological formalism
- A presentation of the first cosmological models
- A description of the first version of the Big Bang cosmology

2.1 Before relativity

Since Galileo, or more precisely G.Bruno[1], there has been a principle of relativity. This principle enunciates the constancy of physical laws, the latter being independent of inertial frames. The idea is that a ship captain in his cabin cannot determine if he is at the dock or calmly moving over the sea. Similarly, an object falling from the crow's nest stops its journey at its base, never mind if the ship is moving, with a constant speed, or not.

Since Newton, a new view of space has been set with universal gravity. Space is absolute, time is absolute and they are disconnected. An extract of Newton's *Principia* on this subject is reproduced in the below sidebar.

[1]Seidengart 2012.

I. Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external, and by another name is called duration: relative, apparent, and common time, is some sensible and external (whether accurate or unequable) measure of duration by the means of motion, which is commonly used instead of true time; such as an hour, a day, a month, a year.

II. Absolute space, in its own nature, without relation to anything external, remains always similar and immovable. Relative space is some movable dimension or measure of the absolute spaces; which our senses determine by its position to bodies; and which is commonly taken for immovable space; such is the dimension of a subterraneous, an aerial, or celestial space, determined by its position in respect of the earth. Absolute and relative space are the same in figure and magnitude; but they do not remain always numerically the same. For if the earth, for instance, moves, a space of our air, which relatively and in respect of the earth remains always the same, will at one time be one part of the absolute space into which the air passes; at another time it will be another part of the same, and so, absolutely understood, it will be continually changed[a].

[a]Newton 1689, p.6.

2.2 Special Relativity and Minkowski space

A the end of the nineteenth century, Michelson and Morley perform a series of experiments[2]. As they are testing the hypothesis of ether, they come across the constancy of the speed of light. The finite character of this value has been known since 1676, thanks to Roemer[3]. From now on, the speed of light in vacuum c cannot be considered infinite any longer, and more importantly, it is a constant. This means that the Galilean law of addition of speed is ruled out, as explained in the next box.

This leads Albert Einstein to enunciate special relativity. He asserts two assumptions: first, all Galilean frames are equivalent, second, c is finite and absolute in all inertial frames.

[2]Michelson and Morley 1887.
[3]Roemer 1676.

In classical mechanics, speeds can be added, due to the invariance under change of referential frame. If an object is thrown away from a moving reference frame, for the exterior observer, their speeds are added. For example, the velocity of the ball thrown in a train measured on the platform, is the speed of the ball in regard of the train plus the speed of the train in regard of the station.

$$v_{\text{⚽🏠}} = v_{\text{⚽🚆}} + v_{\text{🚆🏠}}$$

With relativity, this law has to change, it is not possible to speed up light.

$$v_{\text{💡🏠}} \neq v_{\text{💡🚆}} + v_{\text{🚆🏠}}$$

$$v_{\text{⚽🏠}} = \frac{v_{\text{⚽🚆}} + v_{\text{🚆🏠}}}{1 + \frac{v_{\text{⚽🚆}} v_{\text{🚆🏠}}}{c^2}}$$

This law of transformation of the velocities, due to Lorentz differs from Galileo's one when speeds involved are commensurable with c.

$$\begin{cases} x' = x - vt, \\ t' = t. \end{cases} \tag{2.2.1}$$

Lorentz new transformation laws from a reference frame (F at rest) to an other (F' in motion with a velocity v) are

$$\begin{cases} x' = \dfrac{x - vt}{\sqrt{1 - \frac{v^2}{c^2}}}, \\ t' = \dfrac{t - \frac{v}{c^2}x}{\sqrt{1 - \frac{v^2}{c^2}}}. \end{cases} \tag{2.2.2}$$

Those hypotheses have unexpected consequences. Space and time become relative. Every event has different coordinates according to each observer frame. Two well-known consequences are the dilatation of time and the contraction of lengths so that space-time intervals are conserved. Those examples illustrate the relativity of any measurement for each observer. In 1908, Minkowski interprets special relativity in a flat space with a pseudo-metric [4]. The evolution of the metrics is presented in the next box.

The flat 4-dimensional Euclidian space can be described by a classical metric $ds^2 = dt^2 + dx^2 + dy^2 + dz^2$.
With this, ds, the line-element, is defined from the element of time , dt, and the element of volume, $dx^2 + dy^2 + dz^2$.
Minkowski space is defined as the 4-dimension space with the pseudo-Euclidian metric $ds^2 = -c^2dt^2 + dx^2 + dy^2 + dz^2$[a].
In consequence, distinct events can be separated by a null spatio-temporal distance, if they are on the light cone.

[a] This metric has a signature (-,+,+,+), convention of the present thesis, but the signature (+,-,-,-) is sometimes preferred.

2.3 General Relativity

After his work on special relativity, Albert Einstein (a short biography can be found in the following sidebar) expresses the wish to incorporate gravitation into his theory. To do so, he enlarges the Galilean principle of relativity to the equivalence principle, Einstein's motivation is expounded in the next technical box. Inertial frames in free-fall inside gravitational well cannot be distinguished from uniformly accelerated frames. This is similar to the thought experiment of the elevator falling, itself equivalent to an accelerated elevator.

Albert Einstein was born in 1879 in the Germanic Empire. Quickly he is disheartened by the military discipline in German schools. At the age of 15, he quits school and joins his parents in Italy. During this period, Einstein makes his own education and starts his thinking on the properties of light. He builds his method on the famous thought experiments.

[4] H. Poincaré suggests a similar model two years before, however it goes through history under the name of Minkowski spaceWalter 2008, p.100.

He joins the Polytechnics school of Zurich via the competitive exam. When an engineer, he is already a family patriarch and, to provide for them, he takes employment at the patent office in Bern.

1905 is called his *annus mirabilis*: between March and September, he publishes five articles, each being a physical revolution. In one of them, c, the speed of light, becomes an absolute, therefore having repercussions on the conceptions of space-time itself. The speed of light becomes a universal constant of physics.

After that, Einstein pursues his works by studying the free-fall. He postulates the equivalence between gravity and acceleration. Doing so, he anticipates the curvature of light induced by gravitation. All of that is contained in his general relativity published in 1915[a]. Gravitation is no more a force but a deformation of space-time.

Einstein's life is also marked by his pacific commitment[b]. When, in 1933, he is forced to leave his home, Princeton welcomes him. He leaves Europe and never comes back in the 22 years remaining of his life.

For more information, the author of this thesis recommends the lecture of Etienne Klein[c].

[a]Einstein 1915.

[b]It can be noticed that, in 1933, Einstein moved from an anti-war position to a pro-war position, intending to save the European civilisation.

[c]Klein 2016.

Einstein searches generalized covariance. He obtains it with a generalisation of the Galilean equivalence principle (inertial mass is equivalent to gravitational mass) which becomes Einstein's equivalence principle. This is a bit too strong, covariance can be obtained without the extension of the equivalence principle.
Equivalence = existence of frames locally inertial, thanks to Riemannian geometry.
Covariance = invariance under diffeomorphism.

It takes Albert Einstein years before he reaches the intuition of a local metric field involving a curved space-time and puts his ideas in equations. The revolution suggested by General Relativity means that the gravitation is no longer a classical force but the expression of the curvature of the space-time induced by the presence and the motion of masses.

Einstein obtains a general series of equations. The left-hand side contains information on the behaviour of space-time. The right-hand side is the stress-energy tensor, encoding the properties of the matter: pressure, density, viscosity, etc. Those equations, commented in the next box, can be understood as matter curves space-time and this curvature dictates the motion of particles.

From the metric field, $g_{\mu\nu}(x^\lambda)$, Einstein derives the expression $G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R$, called Einstein's tensor.
This expression is the left hand-side of the equations

$$G_{\mu\nu} = \kappa T_{\mu\nu}.$$

Einstein encodes his theory in equations, written and interpreted by many authors. Friedmann and Lemaître have given a full exploration of their particular solutions when the field equations are applied to the universe as a whole.

Robertson and Walker have studied space-time under other coordinates set, as given in the following sidebar.

In reference to the pioneer works of **F**riedman, **L**emaître, **R**obertson, and **W**alker; current cosmologists derive Einstein equations from **FLRW** metrics given by

$$ds^2 = -c^2dt^2 + a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2(d\theta^2 \sin^2 \theta d\phi^2) \right).$$

However, Einstein has the intuition that as gravitation leads the universe, this one is condemned to collapse. Einstein also interrogates gravitational behaviour at an infinite distance, leading to a complex boundary value problem. He has the idea that the universe has to be static in a sense, it must remain always the same. That is the reason why he adds a term in his equations called the cosmological constant, cf. infra.

Einstein modifies his equations into

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

The cosmological constant[a] λ permits to neutralize the gravitational collapse and to maintain the universe in an equilibrium state. The introduction of the cosmological constant permits also to avoid the stipulation of boundary conditions at infinity.

[a] In the present work the cosmological constant is denoted by λ, in modern notation Λ is preferred.

2.4 Early cosmological models

All the ingredients are present to permit hatching of the so-called modern cosmology. Here are presented the famous first attempts to build a cosmological model. Einstein's model, de Sitter's one, Friedmann's and Lemaître's are expounded in the present section.

2.4.1 Einstein's cylindrical universe

Between November 1914 and June 1916, six articles written by Einstein about general relativity and its application to the whole world can be inventoried.

Einstein's universe possesses a constant curvature independent of time, in which the radius curvature is connected with the total mass of masses existing in space. To conserve the equilibrium state of the universe, Einstein introduces a very finely adjusted constant, λ. In this model, the matter has no own motion.

At every time, it is a spherical, finite, universe with a constant radius, giving a four-dimensional cylindrical universe. This model is presented in more technical details in the next chapter.A technical synthesis can be found in the next sidebar.

In Einstein's model $a(t) = \textit{constant}$, the scale-factor present in FLRW metric which describe the evolution of physical spatial distances, the density is constant and the cosmological constant, λ is also a constant.
The problem and the richness of this spherical static universe lies in its instability. Hence, this model is not physical. The lower condensation produces an expansion or a condensation. The space described by Einstein has no existence, in the physical world.

2.4.2 de Sitter's empty universe

Between 1916 and 1917, Willem de Sitter publishes a wonderful article in three parts, exploring the gravitational and astronomical consequences of Einstein's theory[5,6,7]. de Sitter works with a static universe, the coefficients of the metric being independent of time, and a cosmological constant λ. This model assumes an empty universe. It may appear odd as we observe stars all around us, but, at a large scale, on average, the matter density is so small that de Sitter considers it null. Doing so, de Sitter obtains a spatially flat universe with expanding dynamics. This can be summarised by the following box.

de Sitter's universe is characterised by a null density ρ and a null pressure p, $\rho = 0 = p$.
Thus, the scale factor, $a(t)$ in FLRW metric, has en exponential form and space tends to be asymptotically flat.

2.4.3 Friedmann's dynamical universe

In 1922, from Russia, Alexander Friedmann[8] writes an article about the curvature of space[9]. He discusses only the universe with positive spatial curvature. It seems that he has already considered the scenario of negative spatial curvature but those results are published in 1924.
Friedmann explores the entire space of solutions of Einstein's equations, regarding all the geometries worth considering. He takes the leap not to restrain cosmology to the study of a static universe, with a metric independent of time. The cosmological constant λ is no longer indispensable but can be conserved and studied according to its value. That is how the Friedmann metric was born. A modern version of his equations is given in the box below. For a complete historical review of Friedmann's work, see Luminet's book[10].

[5] Sitter 1916a.
[6] Sitter 1916b.
[7] Sitter 1917a.
[8] Alexander Friedmann is an Anglicism for his original Russian name Aleksandr Fridman
[9] Friedmann 1922.
[10] Luminet 2014, chap.5-7.

By exploring Einstein equation with the parametrisation due to Robertson and Walker, it is possible to express in a modern formalism what is called Friedman-Lemaître equations.

$$\begin{cases} \left(\frac{\dot{a}}{a}\right)^2 + \frac{kc^2}{a^2} - \frac{\lambda c^2}{3} = \frac{8\pi G}{3}\rho, \\ \frac{\ddot{a}}{a} - \frac{\lambda c^2}{3} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right). \end{cases} \tag{2.4.1}$$

where k, the curvature of the spatial section at constant t, describes the geometry.

2.4.4 Lemaître's expanding universe

Independently of Friedmann's work, G. Lemaître investigates Einstein equations. The title of his 1927 publication is self-explanatory *Un univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extra-galactiques*[11]. Doing so, Lemaître is the first to link the solutions of general relativity to the observation of the recession motion of the extra-galactic nebulae. His solutions are a bit more generalist than the previous ones as he considers a possible non null pressure.

Lemaître investigates the links between Einstein's and de Sitter's solutions. He reaches a model which asymptotically, in the infinite past, tends to Einstein's static solution, and is endowed with an expansion process. As Eddington helps the spread of this model in the English scientific literature, this model is known as the Eddington-Lemaître model.

In the original paper, Lemaître finds the law linking the distance and the velocity of the extra-galactic nebulae. Unfortunately, in the translated version, in 1931, Lemaître does not explain his reasoning and just gives the final ratio and its value. It seems that he considers his data (from Strömberg's catalogue) as a bit dated when Hubble's observations are more exact and more reliable[12]. So, this law is called Hubble law, by reference to 1929 Hubble's work, while

[11] An homogeneous universe with constant mass and croissant radius, reporting extra-galactic nebulae radial velocity (Lemaître 1927).

[12] Hubble 1929.

Lemaître predicts and computes it in 1927. This historical confusion between empirical Hubble's relation and Lemaître's prediction has been sorted out on the 26th of October 2018, when the International Astronomical Union voted to recommend renaming the Hubble law as the Hubble-Lemaître law.

In 1931, Georges Lemaître develops the idea of the universe beginning from a primeval atom[13]. If the observed redshift expresses the expansion of the universe, then, in the past, the universe was more compact. From the value of Hubble constant, the age of the universe can be deduced. Yet, with the expansion rate measured at this time, the surmised age of the universe is smaller than some geophysical observations. This incompatibility is called the problem of the age of the universe. To solve this problem, Lemaître uses the cosmological constant and describes his model in three phases. The first period is a decelerated expansion, like an explosion, and can be described as fireworks. G. Lemaître considers this state as a primordial atom, its disintegration generates a process of expansion of the universe. The second phase is an unstable equilibrium between the collapse induced by gravity and the expansion due to the cosmological constant. In the long run, the cosmological constant takes control and induces the third phase of accelerated expansion. The duration of the stagnation period depends on the value of the cosmological constant. For a complete historical review of Lemaître's work, see Lambert's book[14].

> *These theories were based on the hypothesis that all the matter in the universe was created in one big bang at a particular time in the remote past*[a].
>
> [a]Hoyle 1951.

The above excerpt indicates the origin of the term "Big Bang", which is in no way attributable to Lemaître.

[13]Lemaître 1931c.
[14]Lambert 2015.

Part II

Until 1950

Chapter 3

Einstein's Steady-state universe

Having its roots in philosophical speculations, cosmology evolved gradually into a physical science but a science with so little observational basis that philosophical considerations still play a crucial if not a dominant role.

-Robert Dicke-

In this chapter:

- A clarification of the distinction between static and steady-state universes
- A detailed analysis of an Einstein's not so lost draft

The explanation of Eintein's steady-state model developed in this chapter is related to a publication[1].

3.1 Steady-state or Static universe

In a preamble, must be underlined the difference existing between a static and a steady-state cosmological model. The former has no dynamical process. A static universe remains always exactly the same, identical to itself. The latter does not deny a possible dynamical process but remains similar to itself. For example, a river is in a steady-state, it has a dynamics but does not change over time, there are many steady-state processes studied in physics. A steady-state universe evolves with time but some observational measures stay constant.

[1] Dubois and Füzfa 2019.

The nomenclature "steady-state" is not used to indicate that these models deny the dynamics of the universe predicted by Lemaître[2] and measured by Hubble[3]; but, it is a way to dub these cosmological models which postulate a partly unchanging through expanding universe and refute the possibility of any beginning of the universe. Indeed, in these steady-state models, cosmic expansion is achieved with a constant expansion rate, making Hubble's parameter a fundamental physical constant. Evolution is, in some sense, still preserved in the dynamics of space-time and somehow also in the matter content, continuously created so the matter density stays unchanged. The author expounds the technical point of her motivation in the next insert.

The author chooses the term steady-state over stationary to avoid any confusion with stationary space-time. In cosmology, a stationary space-time is characterized by $\delta_t g_{\mu\nu} = 0$, when a static space-time is defined by $\delta_t g_{\mu\nu}$ and a diagonal metric.

The subject of this thesis is no stationary space-time but steady-state universe.

Since the early stages of cosmology, scientists tried to apply the steady-state notion to the universe as a whole system. Some of those attempts deserve to be enunciated here, they are completely expounded in H. Kragh's work[4]. At first, the stationary universe is a problem for chemists. Thermodynamics predicted the heat death of the universe. To avoid it, Svante Arrhenius and Walther Nernst imagined mechanism such as the recycling of radioactivity. In 1918, William Duncan MacMillan, an American astronomer, suggested that the universe never differs from what it was, is and will be. By doing so, MacMillan indicated that the energy, radiated from stars, could be partially absorbed in the *ether* and converted into potential energy associated with a kind of new matter. Next sidebar illustrates how MacMillan arrives to the steady-state universe.

[2]Lemaître 1927.
[3]Hubble 1929.
[4]Kragh 1999, chapter4, section 4.1.

There is no necessary limit to its age, and though the star itself may rise and fall, the universe as a whole is not essentially altered. The singular points may change their positions and their brilliancy, but it is not necessary to suppose that the universe as a whole has ever been or ever will be essentially different from what it is today.[a]

[a]MacMillan 1918, p.49.

MacMillan was not the only one to consider processes of creation of new matter. In 1928, in his famous book *Astronomy and cosmology*[5], the astronomer James Jeans proposed the idea that jets, observed from the centres of galaxies, are the place of emergence of matter already existing in a fifth dimension. Jeans tried to avoid the idea of creation, suspicious for any scientist, with the artefact of pre-existing matter in an unreachable dimension. The same year, Robert Millikan, and his colleague G. Harvey Cameron, explained the observed cosmic rays as the mark of the ongoing creation process[6].

It must be highlighted that Georges Lemaître, famous for his cosmological model, studied Millikan and Cameron's hypothesis[7]. Thus, one can say that even the father of the Big Bang theory studied the possibility of a steady-state model.

3.2 Einstein's lost manuscript

At the beginning of the twentieth century, Albert Einstein's theories of special and general relativity allow the advent of physical cosmology, based on a rigorous background and equations linking together space, time, matter, and energy. Immediately after having published his relativistic equations of the gravitational field[8], Einstein applies, in 1917, his new theory to the universe as a whole while questioning the asymptotic behaviour of gravitation and the associated boundary conditions[9].

[5]Jeans 1928.
[6]Millikan and Cameron 1928.
[7]Lemaître 1930.
[8]Einstein 1916.
[9]Einstein 1917.

Einstein elegantly eludes the problem of choosing the appropriate boundary conditions for space-time by considering the geometry of the 3-sphere which does not require specifying asymptotic behaviour nor boundary conditions. Indeed, Einstein's 1917 model explores a static space-time and, at each fixed time t, the t-space is a 3-sphere. Einstein considers a constant density of matter, ρ. This configuration is unstable [10]. However, to ensure the hydrostatic equilibrium of the cosmos, Einstein has to extend his field equations through the introduction of a new cosmological constant term. Then denoted by $\lambda g_{\mu\nu}$, $g_{\mu\nu}$ is the metric tensor encoding the geometry of space-time and λ is the cosmological constant (nowadays denoted by Λ). This constant can be interpreted as an intrinsic scalar curvature of space-time (i.e. the scalar curvature in vacuum) or a gauge threshold of matter-energy. In the next excerpt, Einstein evokes the introduction of this new constant.

> *That term is necessary only for the purpose of making possible a quasi-static distribution of matter, as required by the fact of the small velocities of the stars*[a].
>
> [a]Einstein 1917, p.432 of the translation.

This new cosmological constant term introduces a new long-ranged force into relativistic gravitation while being compatible with the fundamentals of general relativity: the equivalence principle and general covariance. The cosmological constant term $\lambda g_{\mu\nu}$ later turns out as a non-trivial adding to general relativity, glimpsing at the interplay between quantum mechanics and gravitation. However, Einstein mentions the possibility to move forward without it, especially in his letter to Weyl[11], and discards it in 1931[12].

In 2014, O'Raifeartaigh et al. published a paper[13] concerning a recently discovered attempt by Einstein to build a steady-state model of the universe, a work left unfinished and abandoned before publication[14]. With the help of

[10]This instability can be deduced from the classification of dynamical cosmologies by A. Friedmann in 1922 where the author has shown that Einstein's universe sits at an unstable equilibrium point (see Fig.125-1 of Friedmann's 1922 article (Friedmann 1922)). On this subject, Eddington's book (Eddington 1930a) could also be quoted.

[11]Einstein 1923.

[12]Einstein 1931b.

[13]O'Raifeartaigh et al. 2014, and references therein.

[14]Einstein 1931a.

some experts, the unknown manuscript has been dated as likely written in early 1931. The content of this draft has been studied in several papers, notably in Nussbaumer's publication[15].

The following discussion is based directly on Einstein's original work in 1931, and not on later translations[16].

Despite the cosmic expansion, dynamical property of the universe predicted by Lemaître[17] and observed by Hubble[18], Einstein mentions, in his 1931 draft, that such a dynamical model is unacceptable, without going into any details. Einstein suggests instead a different model, compatible with Hubble's observations but with an average density of matter that is constant over time. Technical aspects of this approach can be found in the next box.

Let us start with Einstein's equations

$$\left(R_{ik} - \frac{1}{2}g_{ik}R\right) - \lambda g_{ik} = \kappa T_{ik} \tag{3.2.1}$$

where g_{ik} is the metric tensor, R_{ik} the Ricci tensor, T_{ik} the stress-energy tensor, R the scalar curvature, $\kappa = 8\pi G/c^2$ and λ is Einstein's notation for the cosmological constant.

The mathematics and notations below are those of Einstein's draft[a] that we chose to reproduce identically here in order to follow Einstein's steps to a stationary cosmology.

[a] Einstein 1931a.

[15] Nussbaumer 2018.
[16] Our French translation of this original draft can be found in the Appendix.
[17] Lemaître 1927.
[18] Hubble 1929.

Using the metric[a]

$$ds^2 = c^2 dt^2 - e^{\alpha t}\left(dx_1^2 + dx_2^2 + dx_3^2\right) \tag{3.2.2}$$

and modelling cosmic matter through the stress-energy tensor of pressure-less perfect fluid

$$T^{\mu\nu} = \rho u^\mu u^\nu$$

where u^μ is the fluid 4-velocity which takes the form, once expressed in the fluid co-moving frame, $u^1 = u^2 = u^3 = 0$ and $u^4 = \frac{1}{c}$.

Einstein first notes the following, incorrect, field equations (temporal then spatial):

$$\frac{3}{4}\alpha^2 - \lambda c^2 = \kappa\rho c^2, \tag{3.2.3}$$

$$\frac{9}{4}\alpha^2 + \lambda c^2 = 0 \tag{3.2.4}$$

where the first[b] and second equations of the above set correspond to the spatial and temporal components of Eqs.(3.2.1), respectively. The system Eqs.(3.2.4-3.2.3) imposes $\alpha^2 = \frac{\kappa c^2}{3}\rho$, leading to a constant density.

[a]In Einstein's draft, a crossing-out can be seen, he corrects only one on the two expressions of the metric to have a signature (+, -, -, -). Furthermore, it is interesting to notice that Einstein uses covariant coordinates and not the expected contravariant ones.

[b]We also reproduce the mistake in the physical dimensions of the right hand side of Eq.(3.2.3).

Einstein argues that, considering a finite physical volume, particles are constantly escaping because of the cosmic dynamics, and therefore some process of continuous creation of matter should exist in order to keep the total matter density constant. Einstein even suggests that these new particles might emerge from space as this latter is not empty due to the presence of the cosmological constant λ. Einstein, therefore, associates the cosmological constant term λ with the creation of matter as, we will see, Hoyle does in 1948[19].

[19]Hoyle 1948.

Unfortunately, the first equation (3.2.4) is wrong and Einstein corrects himself and find [a]

$$-\frac{3}{4}\alpha^2 + \lambda c^2 = 0, \tag{3.2.5}$$

which, together with Eq.(3.2.3) implies that the matter density is indeed constant but trivially zero [b].

[a] The mistake probably lies in the computation of the Ricci spatial component $R_{ii} = \frac{-3\alpha^2 e^{\alpha t}}{4c^2}$ and consequently of the curvature scalar $R = \frac{3\alpha^2}{c^2}$.

[b] If we write down the metric Eq.(3.2.2) as

$$ds^2 = c^2 dt^2 - e^{2\alpha ct}\left(dr^2 + r^2 d\Omega^2\right)$$

with $d\Omega^2 = r^2(d\theta^2 + \sin^2(\theta)d\varphi^2)$ the solid angle element, one can obtain the so-called Schwarzschild-de Sitter metric

$$ds^2 = \left(1 - \alpha^2\bar{r}^2\right)c^2 d\bar{t}^2 - \left(1 - \alpha^2\bar{r}^2\right)^{-1} d\bar{r}^2 - \bar{r}^2(d\theta^2 + \sin^2(\theta)d\varphi^2)$$

through the following change of coordinates

$$\begin{aligned} r &= \bar{r}\left(1 - \alpha^2\bar{r}^2\right)^{-1/2} e^{-\alpha c\bar{t}} \\ ct &= c\bar{t} + \frac{1}{2\alpha}\log\left(1 - \alpha^2\bar{r}^2\right) \end{aligned} \tag{3.2.6}$$

the angular coordinates being unchanged.It could be noticed that in 1917 de Sitter did not already work in the Schwarzschild-de Sitter coordinates (Sitter 1917b)

The solution of the problem posed by Einstein in his draft is, in fact, as explained in the previous technical box, de Sitter's empty solution once expressed in the coordinates found by Lemaître[20].

Before O'Raifeartaigh's work, it was not known that Einstein himself had considered the possibility of a universe fitted with a continuous process of matter creation, this became a central feature of the future steady-state models. Einstein's draft should therefore be considered as the first attempt to build a steady-state cosmological model within general relativity, via his proposal to preserve a constant matter density. Shortly afterwards, Einstein publishes a paper on the cosmological problem of the general theory of relativity in which he finally discards both of his 1917 cosmological contributions. He disowns his

[20] Lemaître 1925, and references therein.

static universe on the grounds that it is unstable. Also, he negates his cosmological constant term, λ, because Hubble's observations could be regarded as more natural in general relativity, without falling back on this term. The aforementioned paper[21], sometimes known as the Friedmann-Einstein model, constitutes the first occasion on which Albert Einstein formally abandons the cosmological constant term, never to re-instate it afterwards.

An analysis and first English translation of the Friedmann-Einstein model has been provided by O'Raifeartaigh and McCann[22]. The evolution of Einstein's cosmological model during the beginning of the 30s is interesting. First, in 1931, Einstein made this aborted tentative of a steady-state expanding universe. Quickly after, he published a model of an expanding universe without any recourse to the cosmological constant. This model is now called the Friedman-Einstein universe. One year later, in a famous work with de Sitter, Einstein considered a model in which both spatial curvature and the cosmological constant were removed.[23]. However, it appears that there is no connection to be made between this published paper[24] and the unpublished one[25]. Einstein's approach can be assimilated to the reasoning principle dubbed Ockham's razor. He tried to integrate the observations into the most simple model.

[21] Einstein 1931b.
[22] O'Raifeartaigh and McCann 2014.
[23] Einstein and Sitter 1932.
[24] Ibid.
[25] Einstein 1931a.

Chapter 4

From Eddington to Dirac

Les savants ne prétendent pas à l'infaillibilité,
c'est plutôt nous, profanes,
qui accordons l'infaillibilité à leurs déclarations.

Le Nuage noir -Fred Hoyle-

In this chapter:

- An introduction to the study of constants in Eddington's work
- A cosmology with two different time-scales
- An analysis of the Large Numbers hypothesis

In this chapter, the journey from the fine-structure constant to Dirac's Large Numbers hypothesis is looked into. The fine-structure constant is, by definition, a pure number i.e. dimensionless. Its precise value could be interrogated and the understanding of its value could lead to a fundamental understanding of nature. For this reason, Eddington chooses to study the fine-structure constant.

At the same period, E.A. Milne tries to reconcile classical Newtonian mechanics and relativity in cosmology. Doing so, he suggests a model of the universe lying on two different sets of coordinates. In particular, he explores the possibility of physics with two time-scales.

At the intersection of those two approaches is Paul Dirac. In 1937, Dirac notices disturbing numerical coincidences. For him, those could, as the fine-structure constant, lead to a better understanding of the laws of nature. To explain them, Dirac develops a cosmological theory based on two sets of coordinates, very similar to Milne's.

4.1 Eddington

In 1916, Arnold Sommerfeld[1] introduces what is currently known as the fine-structure constant. In his study of atomic spectral rays, a particular ratio emerges: the aforesaid fine-structure constant, defined as

$$\alpha = \frac{2\pi e^2}{ch} = \frac{e^2}{c\hbar}.$$

The latter is a fundamental physical constant which quantifies the strength of the electromagnetic interaction between elementary charged particles, identified as a coupling constant. At this time, the set of units used is the CGS system, explaining why α is a dimensionless number [2].
In 2003, Helge Kragh summarizes the enthusiasm and the investigations which emerged with the fine-structure constant[3]. Since α is a pure number, its existence is questionable. For some, it requires an implicit mechanism to set its precise value.

4.1.1 Theory of 136

In his late forties, Arthur Eddington is a famous scientist of serious repute. Surprisingly, at the end of the twenties, he studies the value problem of the fine-structure constant. He seems sure that this dimensionless number can be explained and that its explanation will reveal something about the foundations of science.

While the experiments give a value for the inverse of α about 137, Eddington thinks that it should be 136. Some extracts of his 1929's article *The Charge of the electron* are quite precise in this sense, as it can be seen in the following sidebar.

[1] Sommerfeld 1916.

[2] Nowadays, since scientists work with the International System of units, the definition of the fine-structure constant is slightly different:

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} = \frac{k_c e^2}{\pi c} = \frac{\mu_0 c e^2}{2h}.$$

[3] Kragh 2003.

The experimental value of $\frac{hc}{2\pi e^2}$ *is* 137. *According to the theory proposed in this paper it should be the integer* 136.
I cannot persuade myself that the fault lies with the theory.
We might hesitate between 10 *and* 136 *and* 256, *but not between* 136 *and* 137.[a]

[a]Eddington 1929, p.358.

Working on the cornerstone of electro-magnetism, Eddington studies Clifford Algebra. In this context, working in four dimensions, he needs to consider some degrees of freedom in his model. Doing so, he obtains 10, or 136, or 256 equations. The technical arguments are presented below.

Eddington studies the algebraic description of the wave functions. His works is founded by Dirac's works on the electron in quantum mechanics. The mathematical tool used is the **16** dimensions Clifford algebra, with complex matrices of order four. As Eddington is interested by the interaction between two particles. He has to use the product of two algebras and result with a problem in **256** dimensions.
The situation is invariant considering the exchange of the particles. So, there are 120 indiscernible elements. The problem can be express with **136** remaining terms.

In Eddington's point of view, there is no coincidence, those numbers are fundamental and one of them could be related to the origin of physics. This is the reason why he prefers to consider the fine-structure constant equal to 1/136 either than 1/137 as suggested by the experiments.

4.1.2 Theory of 137

In 1930, A.Eddington revisits his prediction for the value of the fine structure constant, as illustrated in the following box.

I appear to have made such a mistake, and the new prediction is 137[a].
The last term gives the interaction of the two electrons and shows that the value of the constant usually denoted by $\frac{2\pi e^2}{hc}$ *is* $\frac{1}{137}$[b].
I think I have been able to improve my theory of the constant $\frac{hc}{2\pi e^2}$[c].

[a]Eddington 1930b, p.696.
[b]Ibid., p.721.
[c]Eddington 1931c, p.15.

Eddington builds what he calls the theory of 137. In his mind, he has touched the hidden link between general relativity and quantum mechanics. While his interest in this problem is surprising and misunderstood by his colleagues[4], Eddington pursues his idea in his last book[5].

When some think that Eddington is chasing the dream of a theory of everything, he prefers the term harmonisation to unification, as evidenced by the next extract. He looks for fundamental principles lying in the determination of the pure numbers, leaving no arbitrary constants.

I have sought a harmonisation, rather than a unification, of relativity and quantum theory.[a]
The result of these determinations is that there are no arbitrary constants left in the scale of relations of natural phenomena.[b]
[...] *a series of investigations in the borderland between relativity theory and quantum theory.*[c]

[a]Ibid., p.v.
[b]Ibid., p.v.
[c]Ibid., p.121.

[4]Kilmister 1994.
[5]Eddington 1936.

4.2 Milne

During the thirties, Edward Arthur Milne develops his own cosmological model. His motivation is quite particular: he proposes to express cosmological data in a fixed frame. While every scientist tends to interpret the redshift as the physical expansion of the universe, Milne suggests changing the conception from fixed points in a moving space to moving objects in a stationary space.

In 1935, Milne first expounds his model in a book[6]. He develops his theory and responds to some criticisms in a series of eight articles between 1935 and 1938. In 1948, Milne finalizes his model in another book, a sequel of the previous one[7].

4.2.1 Cosmological Principle

To extend astrophysics, or more generally physics, to the whole universe, some strong hypotheses need to be set. Physics lays on the idea that laws of nature are true everywhere and forever. Cosmology requires the same idea, that the universe observed locally is representative of the whole universe. This is called the cosmological principle as Milne dubbed it in the next excerpt.

> *We have only one universe to observe; but we still want the equivalent of a homogeneous universe as a standard comparison, and such standards are provided by systems satisfying the cosmological principle*[a].
>
> [a]Milne 1935, p.70.

Nowadays, the cosmological principle is the assumed homogeneity and isotropy of the universe. Of course, there are various possible interpretations for this principle. From the beginning, Albert Einstein assumes the uniformity of the matter distribution[8]. Moreover, to apply relativity theory, the cosmological principle becomes the descriptions of the system by two observers, in their own measures, coincide. Then, H.P. Robertson used the "intrinsic properties of homogeneity and isotropy attributable *a priori* to such an idealized universe[9]".

[6]Milne 1935.
[7]Milne 1948.
[8]Einstein 1917.
[9]Robertson 1929, p.822.

Quickly, Robertson claimed the paternity of what he calls the cosmological postulate[10], in regard to the cosmological principle coined by Milne. Robertson's approach is summarised in the following technical box.

Robertson assumes the isotropy of the universe and the universality of physical law and obtains the homogeneity of the cosmos.
Isotropy is not really a hypothesis but an implied consequence of observations. It seems that the universe around us, observers, is in each direction similar to itself. The isotropy of the cosmos can be inferred from this assessment, as a rough approximation valid on large scale.
From Newton, physics is based on the assumed universality of its laws. What is true here and now must be true whenever elsewhere.
By combining these two concepts, the observed isotropy must be universal. In conclusion, the universe must be homogeneous around any given two points. That is Robertson's cosmological postulate.

In Milne's description, there is no possibility to have the homogeneity as currently conceived. Indeed, when cosmologists study fixed objects in a mobile space, then the coordinates are changing but the objects are not moving. Milne studies moving objects in space at rest, as expounded in the following sidebar.

In a not static universe, homogeneity would mean that in two points P and Q, at the same time t, the densities $\rho(P,t)$ and $\rho(Q,t)$ are equal. However, applying relativity, there is no more such a thing as simultaneity.

[10] Robertson 1936.

So, homogeneity would mean that the densities in two points are equal at two different epochs. Milne concludes that there is no unambiguous definition of homogeneity[a].
However, the contradiction between homogeneity and relativity is mere appearance. FLRW models and their symmetries imply the existence of a synchronous referential, eliminating the ambiguity of the simultaneity.

[a]Milne 1935.

4.2.2 Temporal scales

Milne's idea is to develop an alternative to relativistic cosmology. In this latter theory, objects are fixed in a moving space and the universe could be described by using the gravitational formalism derived from relativity. Milne prefers a conception of the universe as moving objects in a fixed space. Doing so, he can describe the universe from Newtonian equations coupled with some thermodynamics.

Milne works from the assessment that the first and only truth is the perception of time, the possibility to build a chronology. On the contrary, relativity is based on the existence of several observers and the communication between them about events, which requires the description of the parallel transport of a rigid length scale. This is expressed by Milne in the next citation.

Relativity is the comparison of experiences of different observers. Thus it comes about that we introduce not only the particles we observe, but hypothetical observers on these particles outside ourselves. There is no need to do so. We could survey and describe the universe from ourselves alone, and let the matter rest there[a].

[a]Ibid., p.16.

Milne does not accept this construction. He suggests the use of two sets of coordinates. Especially, he defines two kinds of time scales, t and τ, indistinguishable for our present experiments. The link between these two time scales is expounded in the following box.

The time of dynamical experiences is τ, it is the time of dynamical time-keeper (pendulum, orbiting planets,...). The kinematic temporal variable is t. These two times are linked by $\tau = t_0 log(\frac{t}{t_0}) + t_0$, where t_0 is the present value of the age of the universe.
Today, $\tau_0 = t_0$ and $\left(\frac{d\tau}{dt}\right)_{t=t_0} = 1$. This means that the two temporal scales are indistinguishable at the present time. They imply considerable differences when long amount of time are involved, notably for astronomical phenomena such as the evolution of a stellar system or the study of receding nebulae.

The idea of creation, or beginning of time, loses its meaning as $t = 0$ is equivalent to $\tau = -\infty$. This means that an infinite number of dynamical events has occurred since "the beginning of time".

The redshift of galaxies measured by Hubble can have completely different interpretations regarding the set of coordinates. When lengths or distances are measured on the kinematic scale, t, nebulae are receding. When distances or lengths are measured on the dynamical scale, τ, nebulae are stationary. The ideal measured distance, rigid on the dynamical scales, is no longer rigid on the kinematical scale[11]. Milne's explanation can be read in the next insert.

The epoch $t = 0$ is, in fact, dynamically inaccessible in time, just as the absolute zero of temperature is thermodynamically inaccessible. This is of fundamental evolutionary significance.

[11] Milne 1937a.

That the "age" of the solar system given by radioactive rocks is approximately equal to the "age" of the universe given by the recession of the nebulae, i.e., is equal to the kinematic value of the present epoch, is evidence for the view that a radioactive clock keeps kinematic time t, not dynamical time τ ; by rather more arguments, which will be given later, it will be shown that likewise an atomic clock keeps kinematic time, i.e. emits a frequency whose measure ν_0 in kinematic time is a constant[a].

[a]Ibid., p.328.

4.3 Dirac

In this section, Dirac's steady-state cosmological model is presented. The first steps of his model are expounded in Dirac's letter to the editorial committee of *Nature*[12]. In this letter, Dirac (a short biography of which can be found below) sets the basement of the Large Numbers hypothesis, also known as the Dirac principle. Some months later, Dirac developed a more complete cosmological model deduced from his original idea[13].

Born in Great Britain in 1902, Paul Adrien Maurice Dirac owes his French first name to his French-speaking Swiss father. This strict and austere father shapes Dirac's solitary character. PAM Dirac is not educated in arts or classical studies. He studies engineering in Bristol for some practical and useful reasons. His teachers, noticing his talent for mathematics and physics, push him for a theoretical formation in Cambridge.

[12]Dirac 1937b.
[13]Dirac 1938.

In 1925, PAM Dirac read Heisenberg's articles and joins the quantum field. Isolated from continental quantum teams, he works alone and rediscovers their results. In particular, he explains the non-commutativity by using the formalism of Poisson's brackets. However, he benefits from regular correspondence with Heisenberg, Born, and Jordan too. This is more difficult for the American scientists involved in this new research field, as John Slater.

At the Solvay conference, in 1927, at the age of 25, Dirac has an international repute. However, often, his results are first published by others, as everybody is doing the same research. This changes when Dirac studies relativity and spinning electrons. In 1933, when he is thirty-one, he achieves the dream of all physicists and receives the Nobel Prize with Erwin Schrödinger "for the discovery of new productive forms of atomic theory."

In 1937, the newly wedded Dirac takes an unexpected interest in cosmology. In 1984, Dirac dies in California after a long and fruitful scientific career.

For the anecdote, it could be noticed that Dirac, who did not want students, agreed to be the advisor of F. Hoyle, he who did not want a research director. For more information, Kragh's Dirac biography can be consulted[a].

[a] Kragh 1990.

4.3.1 1937 Letter

The myth says that the 1937 article has been written during Dirac's honeymoon. Indeed, PAM Dirac weds Margit Wigner at the beginning of this year and the letter is dated from the very start of February. Of course, this article enters into history for a completely different reason. Indeed, this letter is famous because unexpected and surprising. A lot of readers wonder how and why those ideas came to Dirac's mind.

In *The Cosmological Constants*, Dirac starts by reconsidering fundamental constants of physics, c, h, e, etc..., noticing that they provide a set of absolute units. Dirac reminds Eddington's interest in the dimensionless numbers built from the constants. Nonetheless, he decides not to consider the fine-structure constant but other dimensionless numbers; namely, the ratio of the electric and the gravitational forces between electron and proton ($\sim 10^{39}$), and the ratio of the mass of the universe[14] to the mass of the proton ($\sim 10^{78}$). The numbers are much larger than the fine-structure constant ($\alpha \simeq 1/137$), so they must require a different kind of explanation.

By considering the age of the universe, at this time valued at 2.10^9 years old, and by expressing it in atomic units [15], Dirac obtains the large number dubbed the epoch (γ), which is about 10^{39}. This could not be a coincidence and leads Dirac to enunciate the first version of the Large Numbers hypothesis, first version repeated here.

> *This suggests that the above-mentioned large numbers are to be regarded, not as constants, but as simple functions of our present epoch, expressed in atomic units*[a].
>
> [a] Dirac 1937b, p.323.

On the one hand, by applying this principle to the ratio of the universe and the proton masses, it can be concluded that the number of protons, and neutrons, must increase proportionally to the square of the time. Of course, there is no physical evidence for such a growth of content in the universe, but physics, at this time, is not able to measure such a slow and small increase. It could be interesting to investigate if this creation of matter occurs homogeneously or in some dense and local spots, such as the interior of stars.

On the other hand, Dirac's principle, applied to the ratio between the electrical and gravitational forces, seems to say that the gravitational constant is not any longer a constant but must decrease with time, proportionally to the inverse of the epoch. So if the gravitational power of an object is its mass

[14] Dirac's letter is very concise, he did not mention the source of those masses neither the possibility of an infinite universe.

[15] With atomic physical constants, it is possible to built an atomic unit of time $\frac{e^2}{m_e c^3}$

multiplied by G, the gravitational power of the universe, and potentially of all its components, should increase like time.

From a certain point of view, this could be equivalent to Milne's cosmology. This is mentioned by Dirac himself in the next quotation. Two time coordinates, t and τ, would characterize two looks on the universe, and in one of them G is not a constant.

This is to some extent equivalent to Milne's cosmology[a]*, in which the mass remains constant and the gravitational constant increases proportionally to* t. *Following Milne, we may introduce a new time variable,* $\tau = \log t$, *and arrange for the laws of mechanics to take their usual form referred to this new time*[b].

[a] Milne 1937a.
[b] Dirac 1937b.

The mixed reception of the 1937 letter is expounded in the next chapter. However, like every letter published in *Nature*, a short synthesis of this letter exists, written by the editors in the section *Points from foregoing letters*. This rather succinct review of a letter that is already not very long can be found in the next sidebar. Nevertheless, all the important elements have been included: the coincidences, their consequences in a variation of G and of the total mass of the universe, as well as the link to Milne's work. Unfortunately, a mere reading of this summary could lead to a misunderstanding of Dirac's general motivation, which is more scientific than it seems at first sight.

By expressing the age of the universe as derived from cosmological theories (2×10^9 *years) in units provided by atomic constants* (e^2/mc^3), *Prof. P.A.M. Dirac obtains a number comparable with the ratio of the electric to the gravitational force between the electron and the proton* (10^{39}).

> *He suggests that this ratio, and also that between the mass of the universe and the mass of the proton (10^{78}) are functions of the age of the universe. This leads him to the supposition that the amount of matter in the universe is constantly increasing while the gravitational 'constant' decreases. He introduces a new time variable ($\tau = log t$) similar to Milne's distinction between 'dynamic' time as measured by pendulums, etc., and 'kinematic' time measured by radioactive and atomic phenomena*[a].
>
> [a]Nature 1937a, Original quotation marks.

4.3.2 1938 Model

At the end of the year 1937, Dirac submits his cosmological model[16], built on the Large Numbers hypothesis, with some general considerations. With Hubble's results, namely the natural velocity of galaxies, it becomes possible to deduce a preferred time-axis and an absolute measure of time, so-called the epoch.

To study cosmology, physicists need some new assumptions. One of them is the cosmological principle, whereby the universe is homogeneous and isotropic. Milne extends those assumptions, by adding the Dimensional Hypothesis, which requires that there shall be no constants with dimensions appearing in cosmological theory. Therefore, Dirac suggests an alternative assumption, less controversial. Dirac picks his principle again and enunciates the Large Numbers hypothesis more formally (see in the next box).

> *Any two of the very large dimensionless numbers occurring in Nature are connected by a simple mathematical relation, in which the coefficients are of the order of magnitude unity*[a].
>
> [a]Ibid., p.201.

Applying it to any large dimensionless number, he can link them with simple functions as explained in the following technical sidebar.

[16]Dirac 1938.

With a and b both of the order 10^{39}, it cannot be concluded with certainty that $a = d.b$, where d is a constant of order unity.
To conserve the numerical coincidences for several powers of ten, d must be allowed to differ from unity. Thus, we must have that $a = db \log b$.
In the present theory, Dirac ignores the possible occurrence of such logarithmic factor. It must be noticed that the theory will be valid only as a first approximation. Dirac predicts that this will need to be modified in future investigation to insert some slowly variable functions[a].

[a] Dirac 1938.

First, Dirac attacks one of the main problems of cosmology, i.e. the law for the rate of recession of galaxies. Of course, the distance between galaxies could be expressed as a dimensionless number and, accordingly, the Large Numbers hypothesis must be applied. The inverse of Hubble's constant itself could be seen as a large number. Those arguments are given in the next box.

Let's denote $f(t)$ the distance between two close galaxies divided by the atomic unit of length. Thus, $f(t)$ is dimensionless and thus varies with the epoch. Hubble's constant, the redshift per unit distance, can be obtain in term of $f(t)$ and becomes himself dimensionless.

With the cosmological principle, assuming the uniformity and the spherical symmetry of the universe, $f(t)$ must be the same for any two close galaxies, except for an arbitrary constant factor. If light is emitted by the first galaxy, setting $c = 1$, the second galaxy receives the light $f(t)$ later.

If the emitted light has a period of δt, the light has a journey of $f(t+\delta t)$ and the received period, by the second galaxy, is $\delta t - f(t+\delta t) - f(t)$. The redshift, namely the change in the period, could be defined by $\dfrac{\delta f(t)}{\delta t} = \dot{f}(t)$. Thus, the Hubble's constant becomes $\dfrac{\dot{f}(t)}{f(t)}$, measured at 1.4×10^{-39}.

This leads to a small age of the universe, about 7×10^{8} years. This value can seem problematic in regard to the age of the Earth, unless the rate of radioactive decay varies with the epoch. The link between the epoch and the recession of galaxies is explained in the next technical sidebar.

With the cosmological principle, it makes sense to work with the average density of matter ρ. Considering the recession of galaxies, it can be seen that $\rho \propto f(t)^{-3}$. Using the amount of luminous matter, ρ[a] can be evaluated 7×10^{-45}. However, it is a rough approximation.

It is more correct to say that H and ρ are of the same order. Doing that, their reciprocal are large numbers so they can be linked by just a factor d, $\rho = d\dfrac{\dot{f}(t)}{f(t)}$.

This equality leads to

$$f^{-3}(t) = p\frac{\dot{f}(t)}{f(t)}.$$

Hence, with an appropriate integration constant, equivalent to setting the zero of time,

$$f(t) \propto t^{\frac{1}{3}}.$$

[a]The average density of luminous matter is then about $5 \times 10^{-31} gcm^{-3}$

Thereby, the velocities of recession are not constants but are proportional to $\dot{f}(t)$, that is to say $\propto t^{\frac{-2}{3}}$. So, the epoch could be calculated from H, $t = \frac{1}{3}\frac{f(t)}{\dot{f}(t)}$.

Secondly, Dirac studies the three-dimensional hyper-surfaces defined by a constant t, called the t-spaces. Thanks to the cosmological principle, postulating the uniformity and the spherical symmetry of the universe, the t-spaces have a constant curvature. One of the main problems of cosmology is to determine if the curvature is positive, negative, or null. Dirac easily disregards two possibilities and obtains flat t-spaces. Dirac's arguments are expounded below.

It is easy to rule out the positively curved t-spaces. Indeed, with positive curvature, the t-spaces are finite, like the three-dimensional surface of a four-dimensional sphere. If the hyper-surfaces are finite, the mass of the universe is finite too. This means that the number of protons, and neutrons, is a fixed large number. Using the LNh, this number must vary with time, in regard of the epoch. Using the conservation of mass, this number is a constant[a]. This obvious contradiction pleads for non-positive curvature.

The case of negative curvature could be ruled out with the same kind of argument, event if it is a bit more tricky. If k is negative, the t-space is infinite and hyperbolic. Thus the mass of the universe is infinite, but it is interesting to study the sphere which the radius is the radius of curvature of the t-space.

[a]Without any motivation, Dirac mentions "*our assumption of conservation of mass*Dirac 1938, p.205

Let's consider two t-spaces, denoted by t_1 and t_2. There is a natural correspondence between the points in t_1-space and t_2-space. The distances are multiplied by the factor $\frac{f(t_2)}{f(t_1)}$ as well as the radius of curvature. However, the mass contained by the sphere at t_1 is equal to the mass contained in the sphere at t_2. As this mass is finite, it corresponds to a number of protons. Using the same argument as before, a contradiction appears between the LNh and the conservation of the mass.

Thus, the only curvature consistent with the LNh is zero. The t-spaces are infinite and flat.

Then, Dirac wants to apply general relativity, which explains gravitational phenomena, to the universe as a whole. However, in general relativity, G must be constant. For this purpose, Dirac suggests the use of another set of units. Defining new length and time units, by dividing the former by the epoch, Dirac builds a set of units in which G is no longer proportional to the inverse of the epoch. Thus, physics needs two sets of units: the conventional for atomic phenomena and classical mechanics and the new one for general relativity. This structure is very similar to Milne's theory to the exclusion of the fact that the ratio between t and τ in Dirac's theory is just the inverse from what it is in Milne's.

Finally, Dirac studies Robertson's equations[17] in his new set of units, this is summarised in the following sidebar. He obtains a consistent result regarding the average density of the universe. And, also, he deduces a null hydrostatic pressure, which could plead in favour of his model since it seems that this pressure could be counted as zero in a first approximation.

Let's denote any quantity in the new set of units by a star *.
$\delta t^* = t\delta t$ hence $t^* = \frac{1}{2}t^2$
The distance between two close galaxies becomes:
$f^*(t) = tf(t) \propto t^{\frac{4}{3}}$ or $f^*(t^*) \propto t^{*\frac{2}{3}}$

[17] Robertson 1933, eq.(3.2).

Robertson's equations could be written:

$$\kappa\rho^* = 3\frac{{f^*}'^2}{{f^*}^2}$$

$$\kappa p^* = -2\frac{{f^*}''}{f^*} - \frac{{f^*}'^2}{{f^*}^2}$$

In the equations, k is null because the t-spaces are flat. And λ is set to zero.

Indeed, if λ is non-null, it must be very small to be in agreement with observation and so its reciprocal is a large number. According to the LNh, if λ is not zero, it must vary with the epoch.
Robertson's first equation can been re-written $\kappa\rho^* = \frac{4}{3}{t^*}^{-2} = \frac{16}{3}t^{-4}$. This result is not a surprise, it is consistent with the previously used $\rho \propto f^{-3} \propto t^{-1}$.
Robertson's second equation becomes $\kappa p^* = 0$. This is an important result as he is in accordance with the observation.

To conclude, the Large Numbers hypothesis allows the construction of a satisfactory theory of cosmology.

Chapter 5

1937 controversy

La recherche est un jeu
que celui qui n'aime pas jouer n'en fasse pas.

-Georges Lemaître-

In this chapter:

- A presentation of the reactions to Dirac principle
- A detailed analysis of the subsequent controversy

The content of this chapter has been partly published in *Revue des Questions Scientifiques*[1].

Dirac's model sparked off some interesting reactions. Indeed, in 1937, Chandrasekhar and Kothari share some coincidences they have noticed, independently of Dirac. Applying the same reasoning, they show other consequences of the possible variation of G.

Furthermore, Dirac's idea was unexpected and surprising from a young Nobel laureate. Herbert Dingle, already initiator of a debate about cosmology in 1931[2], starts a new controversy about Dirac's approach and his epistemological foundations.

[1] Dubois 2021.
[2] H.D. 1931.

5.1 Chandrasekhar Cosmological constants

In May 1937, Subrahmanyan Chandrasekhar publishes an article also entitled *The Cosmological Constants*[3]. Encouraged by Dirac's earlier work, he wants to share some coincidences he has noticed a few years before. With the natural constants, Planck's constant h, the velocity of light c, the gravitational constant G, and the mass of the proton[4] m_p, a series of relations of mass-scale can be built:

$$M_a = \left(\frac{hc}{G}\right)^a \frac{1}{m_p^{2a-1}}$$

where a is an arbitrary numerical constant. Chandrasekhar's reasoning is expounded in the box below.

Working in a homologous stellar configuration[a], the stellar mass must contain the mean molecular weight $(\mu m_p)^{-2}$.

When $a = 2$, then $M_2 = \left(\frac{hc}{G}\right)^2 \frac{1}{m_p^3} \cong 9.5 \times 10^{20} M_\odot$. By dividing this relation by the proton mass, Chandrasekhar reaches a dimensionless relation:

$$\frac{M_2}{m_p} = \left(\frac{hc}{G}\right)^2 \frac{1}{m_p^4} \cong 1.1 \times 10^{78}.$$

This large number can be interpreted as the number of particles in the universe. It leads S. Chandrasekhar to the same result as Dirac: if G is proportional to t^{-1}, i.e. if G is inversely proportional to the epoch, then the number of protons and/or neutrons in the universe, should be proportional to t^2. Therefore, matter must be created over time.

[a] In homologous configuration, it is assumed that all physical variables in stellar interior scale the same way with the independent variable measuring distance from the stellar center. The scaling factor used is the stellar mass, M. Namely, stellar properties vary as $\frac{M(r)}{M}$

[3] Chandrasekhar 1937.

[4] Discovered in 19191 by Rutherford, the proton has been regarded for a long time as an elementary particle

By studying some particular configuration of the relation he underlined and by applying the Large Numbers hypothesis, Chandrasekhar obtains different creation rates. Not only, matter is created as predicted by Dirac, but the rate of creation differs according to the astrophysical scale. S. Chandrasekhar points out three scales and their specific creation rate: stars, galaxies, and the universe (explanations can be found in the following box).

Looking to the relation when $a = 1.5$ must say something on stellar structures:

$$M_{\frac{3}{2}} = \left(\frac{hc}{G}\right)^{\frac{3}{2}} \frac{1}{m_p^2} \cong 5.36 \times 10^{31}\text{kg} \cong 30 M_{\odot}.$$

Which is of the order of thirty times the solar mass. It is also the superior mass limit of the completely degenerated configuration. By applying Dirac's result that G varies as the inverse of the epoch and by considering $M_{\frac{3}{2}}$ representing a stellar mass, the number of particles in a star should increase as $t^{\frac{3}{2}}$.

Moreover, when $a = 1.75$, then $M_{\frac{7}{4}} = \left(\frac{hc}{G}\right)^{\frac{7}{4}} \frac{1}{m_p^{5/2}} \cong 1.7 \times 10^{11} M_{\odot}$, which is of the same order as the Milky Way system mass. So, if $M_{\frac{7}{4}}$ corresponds to the mass of galaxies, by applying Dirac's result that G vary as t^{-1}, we should have that the number of particles matter should be created in galaxy with a rate proportional to $t^{\frac{7}{4}}$.

Nature editorial committee has written a few lines about Chandrasekhar's letter repeated in the next sidebar. The fundamental difference between Chandrasekhar's idea of mater creation and Dirac's is that in Dirac's letter[5] matter must be created in a certain relationship with the age of the universe; whereas, in Chandrasekhar's publication[6], there are different scales of astronomical objects and therefore different rates of matter creation, all functions of the age of the universe. Thus, Chandrasekhar's reasoning depends neither on a coincidence nor on the redundancy of the value 10^{39}, unlike Dirac's. As the relations

[5] Dirac 1937b.
[6] Chandrasekhar 1937.

built seem to be true and dependent on G, if G varies, the relations found must also vary.

Dr.S.Chandrasekhar directs attention to a combination of certain 'natural' constants (the velocity of light, the mass of the proton, the constant of gravitation and Planck's constant, h) which has the dimension of mass. A particular form of this combination occurs in the theory of stellar interiors. By substituting simple values for the arbitrary constant in the formula, the author shows that one can obtain numbers comparable with the mass of the Milky Way, and with the total number of protons and/or neutrons in the universe - such as were derived by Prof. Dirac from similar dimensional arguments[a].

[a] Nature 1937b.

5.2 Dingle's criticism of "Modern Aristotelianism"

A week after Chandrasekhar's publication, Herbert Dingle (1890-1978), physicist and philosopher of science, founder of the prestigious *British Society for the history of science*, publishes an article devoted to what he calls the *Modern Aristotelianism*[7]. Dingle distinguishes two epistemological approaches to scientific work: he contrasts the Aristotelians with the Galileans.

Originally, Aristotelianism is the idea that nature is the expression of general principles known by the human mind without the bias of sensory perception. The Aristotelians act as if the human mind has an *a priori* knowledge of the regulating principles of nature. From this point of view, the reason could deduce the course of experience without resorting to sensation.

From the Galilean point of view, nature is independent. The only thing that the human mind could do is to observe and try to describe what is perceived. The reason could seek to correlate the observations into a logical system and to induce laws.

[7] Dingle 1937b.

By placing these two approaches as opposites, Dingle poses the question of what science is. The question is no longer whether this is the right way to do things or not, but, more importantly, what are the things that need to be done. In other words, should a particular conclusion be deduced from general principles or should general principles be induced from observations? In that way, Dingle interrogates the place of intuition in science.

> *It is no idle boast that until now the thoughts and practices of men of science have been such as Galileo would have approved. Even merely verbal heresies, such as the statement that science is based on faith in an 'Order of Nature' have been few and harmless ; we may have said such things, but we have always acted as though Nature might nothing care for what our minds call order. It is not a light matter, then, when we find in our own day a revival of Aristotelianism in the front ranks of science itself*[a]*.*
>
> [a] Ibid., p.784.

For Dingle, as illustrated in the previous box, Galileo would generally approve of modern science until the thirties, when a revival of Aristotelianism seemed to be witnessed. It is no longer the original Aristotelianism, but an evolved form: idolatry where the Universe is a God. This type of science transcends observations and cannot be obtained by induction from an experiment alone. Dingle is surprised by the general acceptance of this idea and by what seems to be a lack of protest, to say the least.

Herbert Dingle illustrates his point with three famous examples. In the first one, Dingle is interested in Arthur Eddington, who he considers to be an Aristotelian, notably because Eddington interprets the cosmological constant, λ, as a fundamental constant of nature. Dingle emphasises this by quoting directly Eddington. Yet Dingle values his pair enough to be convinced that he is not a slave to chimeras and, in practice, that Eddington refutes his own *credo*. To illustrate this, here is the excerpt from Eddington that Dingle quotes, followed by what he says about it.

There is nothing in the whole system of laws of physics that cannot be deduced unambiguously from epistemological considerations. An intelligence, unacquainted with our universe, but acquainted with the system of thought by which the human mind interprets to itself the content of its sensory experience, should be able to attain all the knowledge of physics that we have attained by experiment[a].

[a]Eddington 1936, p.327.

But Eddington's own practice refutes his creed. He is too great to be the slave of chimeras, and his generalizations are but unsuccessful attempts to utter what he finds inexpressible[a].

[a]Dingle 1937b, p.785.

The second one to be pointed out is Edward Milne. Dingle's criticisms concern the cosmological principle which definition by Milne can be found in the next box. For Dingle, this hypothesis invents a universe to be studied, distinct from the one we observe.

The cosmological principle is not a concealed law of nature but is simply a definition defining the subject of study, just as in any gravitational problem we must define what we are discussing — one-body problem, three-body problem , etc[a].

[a]Milne 1937a, p.325.

Finally, Dingle comes to Paul Dirac, also a victim of the "*great Universe mania*". What Dingle takes away from Dirac's letter[8] is that large numbers

[8]Dirac 1937b.

require a completely different kind of explanations than small ones. He is sceptical and points out that with an infinity of pure numbers, it is difficult to draw a borderline between large and small numbers.

The aim of Dingle's article is to shed light on the old debate about the basis of science, namely whether science is induced from observations or deduced like an invention. Strangely, it seems that Dingle tries to impose a way of thinking, by reneging his own physicist education.

This article provoked a large number of reactions. With hindsight, some details are worth to be highlighted. First, the use of Aristotle as a reference for the deductive approach is questionable. It would seems that Dingle associate Aristotelianism and authoritarianism. As Eric Temple Bell notices[9], this method is more characteristic of a Platonic Pythagorean science. Indeed, this philosophical approach to science is based on a very intellectual conception and, with it, nature can only be embraced by the human mind. Besides, Aristotle, as a man of science, was convinced of the importance and the primordial role of observations and experiments. In choosing Aristotle as the figurehead of deductivism, Dingle makes a historical mistake.

Secondly, Dingle's reaction to the cosmological principle used by Milne can be questioned. This idea is in direct continuity with the principle of the universality of physical laws. Science lays on the assumption that experiments and their results are independent of their spatial and temporal location. Strangely enough, this principle is already present in earlier widely accepted works[10,11], and Dingle only criticizes Milne's application of the cosmological principle.

Finally, even though some elements of Dirac's letter are debatable, the attack on the definition of what is a large number, regarding the infinity, is rather immature and leads one to think that Dingle does not understand Dirac's argument. Dingle seems to be more bothered by the use of the qualifying adjective "large" than by the argument developed by Dirac.

In the light of the above, the reader should remember the particular historic-political context of Europe in 1937. Dingle's attempt to defend a British science can be related to the two contemporary political regimes trying to impose their point of view in every domain, including scientific fields. Dingle is certainly motivated by a kind of nationalism, which could explain the emphasised first charter of the Royal Society. The following debate, here below, gathers only

[9] Temple Bell 1946, p.408.
[10] Einstein 1917.
[11] Robertson 1929.

British scholars, surely pleasing Dingle.

5.3 Nature Supplement

In June 1937, *Nature* publishes a supplement dedicated to the controversy sparked by Herbert Dingle's opinion on Paul Dirac's letter. Indeed, the editorial committee has received a number of reactions after these publications and decided to gather them all into a specific medium.

A similar supplement had already been published in 1931 with the evolution of the universe as a topic. The opening of the debate was signed by the initials H.D., certainly Herbert Dingle himself. This controversy had a larger influence due to the interventions of, *inter alia*, Georges Lemaître (Leuven), Willem de Sitter (Leyden), and Robert Millikan (Pasadena).

Looking back at the 1937 debate, as Dingle criticizes Edward Milne by name, editors decide to publish his response first. Arthur Eddington continues the development by focusing it on the link between physical science and philosophy. Finally, Paul Dirac takes part in the debate, responding to Dingle's reproaches. After these three contributions, a bench of authors is invited to present their views. The conclusion is left to Dingle.

The current section provides an overview of this entire *Nature* supplement. The author of this thesis synthesises all the interventions and comments on them using secondary literature, notably Helge Kragh's volumes and George Gale's works, respectively in collaboration with Niall Shanks and John Urani. Those references are interesting, but never only focused on the 1937 debate.

5.3.1 On the Origin of Laws of Nature - Milne

The first contribution is written by Edward Arthur Milne (1896-1950), British astrophysicist then professor at the Oxford University. It is nothing more than a synthesis of his previous works. Milne confirms the use of the hypothesis that, on average, the universe has everywhere the same properties. However, there is no link here with any physical corpus or with the laws of nature, it is just a matter of economy of thought. Milne studies the consequences of such a hypothesis without resorting to the empirical laws of nature.

When Milne mentions that physics should behave like geometry, it is not an over-mathematisation of science. It is simply the expression of his dream of physics becoming a complete system of axioms and theorems such as Euclidian geometry is one. Moreover, Milne does not deny the role of observations. In fact, they have two goals: discovering, empirically, new theorems and verifying the relevance of the theorems deduced from axioms. Geometry itself was first empirical in Ancient Egypt and based on deduction in Ancient Greece; modern physics, should, according to Milne, combine these two aspects.

On several occasions, Helge Kragh refers to this controversy. In particular, Kragh stresses Milne's firm stance on rationalism and his refusal to bow in front of Dingle's attack[12].

5.3.2 Physical Science and Philosophy - Eddington

The tone of the response attributable to Sir Arthur Eddington (1882-1944), director of Cambridge Observatory, is interesting as he describes Dingle's article as entertaining and admits his great satisfaction of having shocked him[13]. More seriously, Eddington takes interest in the question of the precedence of the general principles. While it is impossible to have an *a priori* knowledge of the objective universe, any knowledge deduced from an *a priori* method cannot be the knowledge of the objective universe. Eddington shows that the laws of nature do not express knowledge of the objective universe. There is no objective element in general laws, especially in observed systems.

Kragh underlines Eddington's satisfaction and briefly reviews his argument[14]. As much is deduced with *a priori* arguments, there is no knowledge of the objective universe. George Gale and John Urani also emphasise the idea that physical laws are subjective because they are always derived from epistemological *a priori*[15]. Several lines of Eddington's reply are repeated in the next insert.

In physical science a priori conclusions have long been anathema. It has come to be accepted as a scientific principle that we can have no a priori knowledge of the universe. Agreed; provided that by 'universe' is here meant an objective universe, as was clearly intended when the principle was framed.

[12] Kragh 1999, p.70.
[13] Eddington 1937.
[14] Kragh 1982, p.100.
[15] Gale and Urani 1999, p.358.

But I have calculated, from example, the mass-ratio of the proton and the electron by an a priori method which does not involve any observational measurements. For present purposes we may assume that the calculation is sound, since criticism has not been directed against any particular step in the argument. What follows? We are given -
(a) It is impossible to have a priori knowledge of an objective universe.
(b) The mass-ratio has been found by an a priori method.
Therefore: Knowledge of mass-ratio is not knowledge of an objective universe.[a]

[a]Eddington 1937, p.1000.

5.3.3 Dirac's contribution

Paul Adrien Maurice Dirac (1902-1984), famous physicist and Nobel laureate, takes also part in the *Nature* supplement[16]. For him, this is a way to respond to Dingle's direct attacks. Dirac's opinion is that science requires a balance between what is built up from observations and what is deduced from speculative hypotheses. Science is made through both approaches and Dirac's 1937 letter[17] implied both these points of view.

Indeed, Dirac bases his work upon astronomical and atomic constants provided by observations. He constructs the "simplest" dimensionless numbers from those natural constants. Dirac is truly bothered by the clustering of the aforementioned pure numbers, in contrast to their potential random scattering. The actual values of 10^{39} and 10^{78} are not meant to be the focus of his study, their redundancy is. This observation leads Dirac to put forward a hypothesis: the clustering of pure numbers is a fundamental natural phenomenon that will last forever. This hypothesis has such consequences that the numbers of the order of magnitude of 10^{39} must grow over time, with the epoch.

Dirac also refers to Chandrasekhar's letter[18]. Once the pointed-out coincidences are accepted, it becomes possible to express the average stellar and galactic masses as being proportional to 10^{39}. Thus, computing the rising rate of stellar and galactic masses as a function of time is easy.

[16]Dirac 1937a.
[17]Dirac 1937b.
[18]Chandrasekhar 1937.

In his biography of Dirac, Kragh discusses this *Nature* supplement[19]. In his view, Dirac's answer is a clear expression of him avoiding the debate. Dirac recognises the importance of both inductive and deductive methods and pledges for a balance between them. He does not further the epistemological aspect of the discussion.

5.3.4 McCrea's contribution

William McCrea (1904-1999), head of the mathematics department at Queen's University of Belfast, also reacts to this quarrel[20]. In his view, Dingle's rhetoric against modern Aristotelianism is typically Aristotelian. First of all, a Galilean would see that the alleged Aristotelian infers properties of the physical world from their knowledge of the system by which the human mind interprets sensitive experiments. A Galilean would focus on the connection between the physical and the human worlds.

Second, Dingle uses Galileo's quote '*Nature nothing careth whether her abstruse reasons and methods of operating be, or be not, exposed to the capacity of men.*[21]'. This is a perfect example of a conception of nature without any observational basis. This would mean that Galileo himself was an Aristotelian.

In McCrea's point of view, Dingle questions the link between mathematical and experimental physics. According to Dingle mathematical physics is new and perverted, whereas, for McCrea, it is just the mathematical consequence of hypotheses. The value of such physics is judged on the simplicity and the number of its hypotheses as well as on the observation of its predictions. In this context, the term hypothesis must be understood in its mathematical acceptance: it must be consistent and not necessarily true. Mathematical physics progresses by increasing the number of its hypotheses and by observing more and more of its predictions. Scientists must be motivated not by the opportunity to taunt colleagues' hypotheses, but by testing their success.

In conclusion, McCrea has the rhetorical precaution of assimilating himself with the fools of a famous proverb: "*fools rush in where angels fear to tread*". This could be interpreted as an admission of ignorance in this huge debate. It could also be read as a warning to those who enter this discussion foolishly.

Gale and Urani, in their review of this bickering, underline the quality of

[19]Kragh 1990, p.232.
[20]McCrea 1937.
[21]This quote is found in Dingle 1937b, p.784, without more precise reference.

McCrea's *argumentum ad hominem*, sending Dingle back in the Aristotelian side[22].

5.3.5 Haldane's contribution

John Haldane (1892-1964), British geneticist, also sides with Milne[23]. He speaks on behalf of biologists and geologists from whom Milne's kinematic relativity could have enormous repercussions, as evidenced by the extract below. He admits that if Milne works without the use of experience, then perhaps Dingle could rise up against him. However, the cosmological principle stated in Milne's articles is not a principle without any recourse to experiments. Indeed, Milne's cosmological principle is a way of expressing that we are not privileged observers of the universe. This can be inferred, for instance, from the observation that our Sun is not a specific star.

Concerning Eddington's underlined citation on a system of thoughts that should be able to reach all the knowledge of physics, Haldane points out that such a system could not be built without sensory experience as it is a highly specialized social product.

> *If the results serve to illuminate the history of geological and organic evolution, we shall be kept too busy to find much time to blame him[a] for a perhaps unduly idealistic account of their origin[b].*
>
> [a]i.e. Milne
> [b]Ibid.

Dingle's intervention will not prevent biologists and geologists from working with kinematic time, on that Haldane conclusion is crystal clear. Gale and Urani interpret Haldane's enthusiasm for Milne's work in the light of the discrepancies between geological and physical estimates of the past duration[24]. Milne's two-time scales could be efficient in this context.

[22]Gale and Urani 1999, p.361.
[23]Haldane 1937.
[24]Gale and Urani 1999, p.360.

5.3.6 Jeffreys' contribution

While his book *Scientific Inference*[25] is in its second edition, Sir Harold Jeffreys (1891-1989), statistician and geophysicist from St John's College, joins the debate[26]. Jeffreys agrees completely with Dingle's point of view. From his background in statistics, Jeffreys provides a set of postulates that will allow any type of observations to be assimilated in a theory, without having to assume that different learning principles are required in different topics.

This system of postulates is satisfactory because: 1) it does not treat any hypothesis as *a priori* certain, 2) it provides methods for choosing between hypotheses employing observation, 3) it estimates the parameters involved in the hypotheses in accordance with the observations, 4) it admits that the decisions could be wrong but that they are made with a certain degree of confidence, 5) it is prepared to correct its bad decisions as science progresses by successive approximations.

In Jeffreys' approach, the current problem of science comes from the belief in a special virtue of mathematics. Physicists forget that mathematics is only a tool used to link postulates and observations. The deduction is only useful because of the investigation of the consequences of admitted laws, it is "*a convenient approximation to induction*"[27].

Gale and Shanks note that Jeffreys backs Dingle for inductive and anti-mathematical reasons[28]. One can see that Jeffreys' argument is more about the role of mathematics than about the epistemological background of the controversy.

5.3.7 Campbell's contribution

Norman Campbell (1880-1949), philosopher of science, bases his intervention on the definition of science by W.H. George, author of *The Scientist in action*: "science is the activity of scientists". By doing so, Campbell stresses that there could be no heresy in science but only orthodoxy[29]. If certain speculations can be received as fantastical or metaphysical, the question is not whether they are detached from the tradition of the seventeenth century, but why new ideas have appeared so suddenly.

[25] Jeffreys 1931.
[26] Jeffreys 1937.
[27] Ibid., p.1005.
[28] Gale and Shanks 1996, p.290.
[29] Campbell 1937.

According to Campbell, the new development could have been predicted. Indeed, physics is built by two complementary activities carried out by two complementary profiles: on the one hand, experimenters who do not develop any theory; and on the other hand, theorists who do not carry out any experiment. For a long time, physicists were alternately experimenters and theorists, but lately, physicists have become specialised.

The experimenters work with induction, they find demonstrable experiments and their description by some laws. The experimenters grow their knowledge by accretion. The theorists build theories to explain laws. Alas the meaning of what is an "*explanation*" is subject to fashion. Nonetheless, it is always a question of substituting acceptable ideas for less acceptable ones. For the time being, the theoretical process is divided into three stages: formulating hypotheses, deducing consequences from them, and translating these conclusions into proposals. The particularity of scientific explanations is that they often predict new laws in addition to explaining old ones.

Until the beginning of the twentieth century, physics worked with analogies and mechanical theories. Campbell notices that this methodology has changed and that hypotheses are now expressed in a more mathematical language. In this, Dirac is in direct continuity with the historical evolution of science, and Dingle's criticism is meaningless.

Gale and Urani comment on both logical and historical responses made by Campbell[30]. His argument successfully indicates that the emergence of deduction in science is understandable and does not constitute a breach in history of science at all.

5.3.8 Filon's contribution

While not totally agreeing with Dingle's position, Louis Filon (1875-1937), professor at the University College of London, welcomes the protest against the current tendency in physics to proceed from abstract mathematical theories[31]. Facts and observations lead to particular laws, step by step, using induction. Those who try to solve the whole problem of nature by mathematical deduction, do not explain nature, they simply explore the human mind. According to Filon, it is time to return to the safer methods of the nineteenth century.

[30] Gale and Urani 1999, p.360.
[31] Filon 1937.

As Gale and Shanks note, not all mathematicians defend the method of Eddington, Milne, and Dirac[32]. Filon sides with Dingle against those who believe that the problem of nature can be solved by using only mathematical intuition.

5.3.9 Peddie's contribution

Scottish physicist William Peddie (1861-1946) sees in Dingle's contribution the idea that it might be time to change the (metaphysical) line of attack of physical problems[33]. His text is short and abstruse. He seems to say that instead of blaming the laws of thought for the structure of the universe, we can blame the objective physical universe for the formal laws of thought. So we are no longer Aristotelian, but back in the Galilean and Newtonian science.

As expressed by Gale and Urani, Peddie's goal is to take physics back on empiricist foundations[34].

5.3.10 Sampson's contribution

The astronomer Ralph Allan Sampson (1866-1939) also intervenes in the supplement[35]. His stance is based on a simple observation: we, humans, are limited, our senses are limited and they are our only links with the world. Even our time is limited. Thus, he is not an Aristotelian, because nobody can be.

Even people who claim to be Aristotelian are not. As human means are limited, it is not possible to make an absolute statement. Moreover, if the theories are written in mathematical language, there can be no question of time. Mathematics is not equipped to express time. In science, we have to deal with theories that express only the essence of what we want to express. Each statement is extrapolated from an experiment, which is itself nearly correct.

5.3.11 Darwin's contribution

In turn, Charles Galton Darwin (1887-1962), mathematician attached to Cambridge and grand-son of his famous homonym, joins the squabble[36]. According to him, what is important in Dingle's publication is not the criticism of Aristotelianism, but the resurgence and persistence of the questioning of the curious

[32] Gale and Shanks 1996, p.290.
[33] Peddie 1937.
[34] Gale and Urani 1999, p.364.
[35] Sampson 1937.
[36] Darwin 1937.

relationship between metaphysics and science.

On the one hand, philosophers have developed metaphysics that underpins all possible knowledge and, in particular, scientific knowledge. If metaphysicists could say what we are allowed to think, perhaps they could put an end to this controversy.

On the other hand, scientists have their own philosophy, rarely being educated in philosophy. This does not prevent them from holding their opinion with polemical enthusiasm. However, the philosophical stances of scientists differ greatly.

Darwin reminds us that both Dingle and Milne will go down in history for their scientific works, without any connection with their metaphysical views. Their philosophy of science could be revealed by an expert philosopher using Socratic maieutics. And, this would expose the inconsistency and impossibility of each of their systems.

Returning to the issue at hand, Darwin does not want to take sides. Dingle's stand in favour of induction and against deduction is difficult to maintain. If Dingle criticizes Dirac's prediction of the age of the Earth based on numerical coincidences, what does Dingle have to say about Maxwell's intuition that the ratio between electric and magnetic fields must be the speed of light. And Dingle's antagonists, who argue that nature and its laws are embedded in our minds, do not make a very important statement. Just because you have the rules of chess constantly in mind, does not mean that you will always win.

Helge Kragh underlines Darwin's choice not to take an active part in the debate[37]. While he is not a supporter of Dirac's approach, he does not espouse Dingle's virulent attack.

5.3.12 Whitrow's contribution

The young Gerald Whitrow (1912-2000), Ph.D. student in Oxford, participates in the debate[38] certainly to defend his mentor Milne, but nevertheless, with quite an argument. In his reading of Dingle, Whitrow sees an attack on the mathematical method of investigation in general relativistic cosmology and a refusal to admit that it is an interesting subject for science because it is based on both experiments and reason. Dingle is said to have an erroneous point of

[37] Kragh 1982, p.101.
[38] Whitrow 1937.

view on, a mythical interpretation of, what really is the history of science.

Whitrow imagines Dingle as an empiricist in the Copernican era. The Copernican model would only be a pseudo-science, a "cosmythology". Dingle would surely prefer the Ptolemaic model based on induction. Dingle seems to forget that Kepler's strength stood in his belief in the existence of a mathematical harmony in nature. Galileo himself used mathematics as a tool for scientific investigation and only evoked experiments to respond to his detractors. Galileo's excerpt quoted by Dingle was only written against scholastic teleology. For Galileo, nature is comprehensible to man through his mind.

Since Copernicus, so-called modern science has been based on three convictions: first, the simplicity and uniformity of nature, second, the mathematically feasible description of nature, and third, the rejection of anthropocentric concepts. Milne, vehemently attacked by Dingle, because of his cosmological principle, is in line with the Renaissance and modern science.

Gale and Urani highlight the excellent methodological argument developed by Whitrow[39]. Indeed, Dingle's idealised, mystical, interpretation of the history of science could be blamed. Whitrow shows that, in his view, Dingle did not understand Galileo and perhaps projects his ideas on him, turning Galileo into a figurehead.

5.3.13 McEntegart's contribution

William McEntegart (1891-1979), *s.j.* teaching, among other things, Thomist cosmology at the Heythrop College in Oxfordshire, points out a philosophical misunderstanding[40]. He wonders why Dingle chooses Aristotle to represent deductive physics. This kind of scientists could be dubbed Kantian, Hegelian, or Fichtean but not Aristotelian. Indeed, on this issue, Aristotle would have agreed with Dingle and support his stance against deduction.

According to Gale and Urani, McEntegart does not take sides in the controversy and simply expounds a historically incorrect use of the term "Aristotelian"[41]. However, one might consider concluding with the idea that Aristotle himself would have been on Dingle's side as quite ironic.

[39]George Gale and John Urani (1999). *Milne, Bondi, and the second way to cosmology.* chapter in The expanding worlds of general relativity. Springer, p.362.

[40]McEntegart 1937.

[41]Gale and Urani 1999, p.358.

5.3.14 Stafford Hatfield's contribution

Henry Stafford Hatfield (1880-1966), author of *The Inventor and his world*, makes the unconventional argument that Dingle has overlooked an important factor in the progress of science: the attractiveness to brilliant minds[42]. Geniuses prefer to concentrate on those areas that leave the most room for creativity. Most of the great minds combine a rigorous approach to facts and reasoning with imaginative speculation. Just being Galilean, as Dingle defines it, would have allowed very few geniuses to be recruited.

The authors Gale and Urani notice the very pragmatic point of view developed by Hatfield[43]. Even if his remark is valid, it is not of great importance in the problem of the epistemological status of induction and deduction.

5.3.15 Dawes Hicks' contribution

According to Georges Dawes Hicks (1862-1941), professor emeritus of philosophy, the strength of Dingle's intervention lies in the justifications he raises against certain ways of presenting the physical world[44]. However Herbert Dingle blames the wrong things, he distorts the deeper meaning of terms such as Galilean or Aristotelian.

Aristotle is not a paragon of reasoning from general principles. On the contrary, Aristotle did not work *in abstracto* but from experiences, through what matter could provide as sensibly perceivable. Aristotle never questioned the validity of sensitive data. By crystallizing an alleged opposition between the Galilean and Aristotelian scientific approaches, Dingle fails to correctly describe what he reproaches modern physics.

5.3.16 Deductive and Inductive Methods in Science : a Reply - Dingle

To close the debate taking place in *Nature*, Herbert Dingle has the opportunity to respond to all previous reactions[45]. First and foremost, he clarifies his idea. His previous publication is not an attack and he stresses his utmost respect for Milne. Then, he recalls that his first use of the term Aristotelian was in inverted commas, the aim being to characterize those whom Newton and Galileo

[42] Stafford Hatfield 1937.
[43] Gale and Urani 1999, p.359.
[44] Dawes Hicks 1937.
[45] Dingle 1937a.

called Aristotelian and not the true followers of Aristotle.

Dingle wants to make a distinction between what McCrea calls mathematical hypotheses, which could be linked to axioms, and what they used to be in Newton's time, when mathematics was cruder. It is important to clarify to which meaning of mathematical hypothesis Milne's cosmological principle is related. Dingle defines science as the discovery of the truth about nature. The whole question is do "*we discover the truth about nature in a rational way, i.e. without resorting to experience?*". The basic conflict between induction and deduction is, according to Dingle, won by induction.

Regarding Eddington's reaction, Dingle is pleased that they agree to the impossibility to *a priori* know an objective universe. However, Herbert Dingle is not sure that Eddington applies this idea in his work. Dingle fears that it would be misunderstood by Eddington's readers.

In Dingle's approach, it seems that Milne is not interested in science at all, he just wants to make a theory. Milne's model does not conform to Dingle's definition of science. In response to Whitrow, Herbert Dingle points out the confusion made between the inaccurate, in conflict with facts, and the irrational, in conflict with reason. One could underline that Dingle does not mention any of the four contributors baking his side (Jeffreys, Filon, Peddie, and Hicks).

On Darwin's reaction, which is assessed by Dingle as an argument to devalue what one thinks of science as long as one allows it to progress; Dingle offers a snap judgement: it does not matter what you burn as long as you make a good fire. This last statement clearly illustrates the dialogue of deaf that takes place in this *Nature* supplement.

Not only this debate does not prevent Dirac from pursuing his cosmological study based on the Large Numbers hypothesis, as it has been expounded in the previous chapter; but also, it does not avoid Dirac's idea to percolate. The following chapters present models directly inspired by the Dirac principle. As for the questions of the constants themselves and their variability, they are always studied nowadays. Jean-Philippe Uzan and Roland Lehoucq's book[46] can be quoted as a modern reference, as well as John Barrow's work[47]. Uzan continues this study in the context of the experiments on the constraints for

[46]Uzan and Lehoucq 2005.
[47]Barrow 2005.

the gravitational constant value[48].

1937 quarrel is largely unknown. However, it is an important example of the consequence of epistemological opinions in the development of science. Most of the participants are from what is called hard science and they take part in the debate and question the intuitive or deductive tenets of science. The author of this thesis would like to highlight this debate for what it is, a philosophical conversation lead by scientists, as these two fields are interconnected.

5.4 Cosmological and Atomic Constants by Kothari

A year later, following Dirac and Chandrasekhar, Kothari publishes in *Nature* his own work on constants[49], without any reference to the debate. Kothari applies the Dirac principle to stellar structures. He deduces the variation through time of the maximal configuration arisen from the theory of white dwarves. His reasoning is presented in the following technical box.

Kothari highlights other relations between physical constants, and works with two dimensionless numbers:

$$\gamma_1 = \frac{e^2}{m_p^2 G} \sim 1.23 \times 10^{36} \text{ and } \gamma_2 = \frac{\hbar c}{m_p^2 G} \sim 1.87 \times 10^{33}$$

where m_p is the mass of the proton (and m, used later, is the mass of the electron[a]).

[a] A reminder: to have dimensionless numbers built this way, you need the charge expressed in StatCoulomb: $\left[\frac{g^{1/2}cm^{3/2}}{s}\right]$

[48] Uzan 2011.
[49] Kothari 1938a.

It must be noticed that $\frac{\gamma_2}{\gamma_1}$, being the inverse of the fine-structure constant α, is evaluated around 137[a].
From the theories of white dwarves and of pressure ionization, a maximum radius R_{max} and its corresponding mass M_{max} could be determined for a cold body of degenerated matter (Fermi-Dirac). Kothari underlines that the temporal variations studied by Milne and Dirac imply variation of R_{max} and M_{max}.

[a]There is a problem, or a mistake, here: Kothari wrote $\alpha \equiv \frac{\gamma_2}{\gamma_1} = \frac{\hbar c}{e^2} \sim 137$; that is the definition and the value of $\frac{1}{\alpha}$. However, mainly, dividing the given values of γ_2 and γ_1, their ratio are not at all of the order of 137.

The *Nature* editorial committee has written few lines about Kothari's letter[50] repeated in the next sidebar. Surprisingly, no one points out the obvious numerical problem of the ratio suggested by Kothari. This article does not bring anything new, just a few other physical quantities varying with time, just like G.

Further numerical relations between fundamental atomic constants and the universal gravitation constant, which coincide roughly with values ascribed to the number of particles in, and radii of, the galaxy and the universe are pointed out by Dr. D.S.Kothari[a].

[a]Ibid.

[50]Nature 1938.

Chapter 6

Jordan

In answer to the question of why it happened,
I offer the modest proposal that our Universe
is simply one of those things which happens from time to time

-Edward Tryon-

In this chapter:

- A presentation of Jordan's motivations
- A detailed analyse of Jordan's cosmological model
- A model of star creation

Introduction

In the continuity of Eddington's research for the fundamental meaning of physical constants and Dirac's letter, Jordan pursues the work by suggesting a new cosmological model. Jordan is a successor of Eddington because he studies physical constants, in the hope of finding a hidden link between quantum mechanics and general relativity. Since the fine structure constant is defined by h, Planck's constant used in quantum mechanics, and by c, speed of light primordial in relativity; by explaining the specific value of the fine structure constant, Jordan glimpses a unified theory.

Descended from an old Spanish family, Pascual Jordan is the first-born of a German Christian couple. Early interested in science, he is one of the founders of quantum mechanics. He is only 23 when he co-signs the famous three-man paper [a].

The rumour has it that, without M. Born's oversight, one of Jordan's drafts should have set what is currently known as the Pauli exclusion principle. His career has however some difficulties to take off. Because of emotional stuttering, Jordan has poor abilities for oral teaching. He was an excellent writer and dedicated some of his time to redact famous outreach works.

Christianity was really important to Jordan. On the other hand, he was a supporter of Copenhagen view of quantum physics from the beginning, deeply positivist. Jordan structure these two positions according to the teaching of Bernhard Bavink, a philosopher and teacher of physics. According to him, modern science had destroyed materialism and thereby broken the walls separating science and religion[b].

Traditionalist, Jordan is said to be frustrated by the treaty of Versailles and worried about the Bolsheviks. This would be the reason why he joins the NS party. However, mainly because he is not anti-Semitic, he gains nothing for his involvement. Indeed, after this political choice, Jordan suffers years of scientific isolation. With his denazification effort, he is jobless for two years after the end of World War II. He waits till 1953 to obtain a full-time teaching office with all its responsibilities.

[a]The *Dreimännerarbeit* by Born, Heisenberg and Jordan laid the foundation of the mathematical formalism of quantum mechanics (Born, Heisenberg, and Jordan 1926).

[b]Jordan 1963.

His personal history costs him the Nobel Prize in physics and turns Jordan into an unsung hero of science. His ideas could be famous and known as important, innovative, and founding quantum mechanics, but his personal choices link him to the dregs of humanity.

To build this presentation of P. Jordan, the author of this thesis bases herself on some biographical works[a, b].

[a] Schroer 2007.
[b] Kragh 2007.

Jordan (introduced in the previous box) has a trajectory similar to Dirac's one. Both of them are important pioneers in quantum mechanics. Both are short-listed for a Nobel Prize, even if Jordan never receives this honour. In cosmology, Dirac and Jordan both have studied large dimensionless numbers and their interpretation. They conclude with a cosmological model built on varying gravitational constant G and continuous creation of matter.

6.1 Units system

To attack the problem of cosmology, Jordan tries to build a system of units consistent with this particular field of physics. To that end, he focuses on five numbers to characterize the universe. Two of them are determined by measurements, the speed of light c and the relativistic gravitational constant κ; two of them are estimated from observations, ρ the average density of the universe and H Hubble's constant; the last one is roughly fixed at an order of magnitude, A, the age of the universe. With these five numbers, Jordan builds two pure numbers, $H.A$ and $\frac{H}{c\sqrt{\kappa\rho}}$. Both of them are of the order of magnitude of unity. It is a kind of validation that they are coherent to constitute a system of units for a well-posed problem. Following Planck's lead, Jordan suggests a unit system. For the mass, he sets $M = \frac{1}{\sqrt{\kappa^3\rho}}$, for the length, he uses what he calls the radius of the universe $L = \frac{1}{\sqrt{\kappa\rho}}$ and, for the time, he simply uses the age of the universe A.

The unit system built, and presented in the next sidebar, is comparable to the atomic unit system, in which the mass is m_p, the atomic length $\frac{e^2}{m_e c^2}$, and the atomic time is just the atomic length divided by c. Studying the ratio between the different systems of units, Jordan arrives at some conclusions similar to Dirac's ones.

$$\frac{M}{m_p} = \frac{1}{m_p\sqrt{\kappa^3\rho}} = 10^{79}$$

$$\frac{L}{\text{atomic length}} = \frac{m_e c^2}{\sqrt{\kappa\rho}e^2} = \frac{A}{\text{atomic time}} = 10^{41}$$

The ratio of these two ratios is an pure number, independent of ρ and equal to 10^{39}

With a physicist approach, involving the determination of natural units in which to study a problem, Jordan reveals some large numbers. Applying Dirac's principle, he has to let the constants, such as G, vary through time.

6.2 Variation of G

The ratios studied in the previous section recourse to the relativistic gravitational constant κ, and therefore to G. A manner to preserve the order of magnitude of the ratios, as Dirac does it, is to let G evolve through time.

The reader does not have to be disturbed by this idea. It is reasonable to consider it and, perhaps, it is an explanation equivalent to the expansion of the universe. Jordan makes an important link to Sambursky's work[1]. Surprisingly, it appears that Jordan is the only author to quote Sambursky, from the Hebrew University of Jerusalem, Palestine, at this time[2].

For Samuel Sambursky, the homogeneous spatial distribution of nebulae indicates that the universe is static. To retain a constant radius of the universe, the electron radius and other universal lengths have to shrink with time, as the following quote indicates. Sambursky's reasoning is then presented.

[1] Sambursky 1937.

[2] Except Sambursky himself in his following work (Sambursky and Schiffer 1938).

The dynamics of expansion are transferred into the dimensions of atomistic phenomena[a].

[a] Sambursky 1937, p.335.

Since there are two universal lengths, $\frac{e^2}{mc^2}$ and $\frac{\hbar}{mc}$, whose ratio is the fine structure constant; and assuming that there is a constant such as c, then h ought to decrease with time and e^2 diminish at the same rate as h does. Therefore, Sambursky suggested a static universe with h decreasing, equivalent to an expanding universe with a constant value of h.
In modern physics, the studies of variable h are included in the Generalized Uncertainty Principle.

Thereby, Sambursky somehow explains the Doppler's effect measured for galaxies. By preserving the Planck-Einstein relation $\varepsilon = h\nu$, it becomes manifest that the old stars emitted light when h was larger, so the emitted frequency ν was smaller and was transmitted to us without undergoing any change. Thus, the observations interpreted as a redshift of the emitted light are no more than the genuine frequency of emission, evidence of the variability of h, as indicated in the next technical box. In modern science, h takes place in numerous micro-physics constants and is considered a fundamental constant.

Sambursky propounds a value for $\dot{h}$ of $-1,03 \times 10^{-43}$ erg[a], working with an expansion speed, based on Ten Bruggencate's work[b], of a value of $486 \, \frac{\text{km}}{\text{s Mpc}}$.

[a] That is equivalent to $-1,03 \times 10^{-36}$ J.
[b] Bruggencate 1936.

Sambursky rejects the idea of a complete linear shrinkage and suggested that h should vanish asymptotically for $t = \infty$.

By posing $h = h_0 \exp(-kt)$, the ratio[a] $\dfrac{\dot{h}}{h} = -k$ enables to evaluate the Hubble factor.

From a strictly dimensional point of view, G can be written as $G = \frac{2\pi e^2}{M^2 mc^2}\dot{h}$. And so, it can be witnessed that

$$\frac{GMm}{e^2} = \frac{2\pi\dot{h}}{Mc^2}.$$

Noting that, it becomes obvious that the relation of the gravitational energy of the hydrogen atom to its Coulombian energy (the left hand of the equality) could be expressed by the rest energy of the atom and $\dot{h}$.

So, G is no longer a constant, it is proportional to $e^2 h$ which decreases as h^2, since e^2 behaves like h. And, as the creation of stars and stellar systems is determined by the product GM (where M is the mass of the system), the masses of the stars that arose back in time must be smaller given that G was greater.

[a]Be careful, in the original paper, the minus symbol is missing.

As Sambursky's ideas have been delineated, here comes the time to go back to Jordan's papers and his reaction to Sambursky's work. Since 1938, Pascual Jordan is echoing Sambursky's approach[3], as it can be seen in the next sidebar. In Jordan's heuristic interest, Sambursky's procedure is completely acceptable. Going back and forth between the expanding universe with constant h and the static universe with variable h is always possible.

[3]Jordan 1938.

Jordan displays a new way to reach the variability of G. As $\kappa \cong \frac{R}{M}$ and because R divided by the element of length, Λ, is equal to γ, the epoch[a], and with M divided by m_p, the proton mass, is γ^2; it could be written that $\kappa \cong \gamma^{-1}\frac{\Lambda}{m_p}$. The relativistic gravitational constant κ is not constant anymore but shrinks as the inverse power law of the epoch and so does G [b].

[a]Since Dirac's letter in 1937, the epoch γ is a dimensionless number defined as the age of the universe divided by a time unit, in most cases the atomic time.

[b]Jordan prefers the notation f for the Newtonian gravitational constant.

6.3 Creation

A direct consequence of Jordan's assumptions is the spontaneous creation of matter[4]. Since the beginning of Jordan's cosmological quest, he has in mind the problem of the creation of matter. If it was quite unclear in his first attempt[5], he grounds this idea on the observation of objects of diverse ages in the universe. If stars or galaxies have different ages, they must appear at different moments and so be created at different times. In 1938, Jordan turns away from G. Lemaître, who refused a continuous production of cosmic radiation. Jordan wonders how Einstein's equations must be modified to account for the continuous creation of matter[6]. In 1939, as observations show older and younger stars, he deduces that the matter emerges directly in the form of stars[7]. To maintain the total energy of the universe, Jordan suggests that the created star equilibrates its positive rest energy with its negative gravitational potential energy (cf. next technical box).

[4]The author of the present work has decided to use the term *creation* in order to put it echoed with following Bondi and Gold, and Hoyle's models. However, the German word is not *Schöpfung*, nor *Erstellung*, neither *Kreation*. Jordan used the name *Entstehung* which is closer to the translation *emergence*. This has nothing to do with a theological or metaphysical *ex nihilo* creation, but concerns more a producing process from a substratum. Nowadays, the concept of emergence is very used in the science of complex systems.

[5]Jordan 1937.

[6]Jordan 1938.

[7]Jordan 1939a.

This result is based upon the gravitational binding energy in Newtonian gravity $U = \frac{3GM^2}{5R}$, which is the energy to provide in order to destroy a gravitationally bound system, under the assumption that it is a spherical mass of homogeneous density.

$$\text{Rest energy} + \text{gravitational potential energy} = 0$$

$$M_\star c^2 - \frac{3}{5}\frac{GM_\star^2}{R_\star} = 0$$

$$R_\star = \frac{3}{40\pi}\kappa M_\star$$

Such created stars are characterised by $\frac{R_\star}{M_\star} = \frac{3\kappa}{40\pi}$.

Jordan's idea is to equal the rest energy (Mc^2) with the gravitational binding energy. Unfortunately, this gravitational binding energy in the strong field regime of general relativity, *id est* of compact objects, is still an open question nowadays. Jordan conceals his use of a Newtonian concept while working in relativity.

Moreover, Jordan comes to the creation of stellar objects with a certain ratio between their mass and their radius, without any condition on their scale. With a modern eye, the compactness[8] of these created stars could be computed. These stars have a compactness of $\frac{5}{3}$, making them not luminous at all since their compactness is larger than the one of black holes[9]. In some way, Jordan develops a model of black hole creation, which has foreshadowed primordial black holes in cosmology.

The absence of comment from Jordan on the mechanism of this creation process is regrettable. Indeed, he establishes the relation between the mass and

[8]In current notation, compactness is defined as $\Xi = \frac{GM}{c^2R} = \frac{R_s}{2R} \simeq \frac{R_s}{R}$, where R_s the Schwarzschild radius. With this convention, the compactness of a black hole is 0.5 and of a neutron star is 0.1.

[9]Gourgoulhon 2004.

the radius of a possible created star without explaining the creation process in itself.

6.4 And then

Jordan pursues the study of his pet-theory during the fifties. Especially, he suggests some experiments to collect data able to certify or disproof his cosmological theory.

For example, the precise measurement of the Sun-Earth distance could provide a good indicator. Indeed, if G varies, the Sun-Earth distance must vary too. In the same manner, the radius of our planet must change. A precise measurement study should be scheduled. Moreover, the study of the morphology of the Moon could also bring into light the reality of the variability of G. With a larger value of G, the Moon could have an atmosphere and potentially tectonic plates. Lunar geology, with volcano activities, could explain the presence of craters on the surface of the Moon. Those observations are currently explained by impacts. Regarding the tectonic motions, geophysicists nowadays explain them by the presence of water and a liquid mantel beneath the crust.

Jordan's post-war work passes to posterity, not for his cosmological model with varying G and matter creation, but for his projective cosmology. Nowadays, Jordan is known thanks to his scalar-tensor theory. Indeed, already in 1947, Jordan follows Kaluza and Klein's ideas. Jordan suggests working with a five-dimension space-time described with tensors by adding a scalar field translating the variation of G[10]. Jordan continues his development in some famous papers[11,12]. Carl Brans and Robert Dicke pursue the study of this idea of scalar-tensor formalism[13]. This model is currently known as the Brans-Dicke theory of gravitation (sometimes the name Jordan-Brans-Dicke theory of gravitation is preferred). Relatively recently, Brans signs an interesting review on this subject underlying the modern challenges for scalar-tensor theories[14].

[10] Jordan 1947b.
[11] Jordan 1948.
[12] Jordan 1959.
[13] Brans and Dicke 1961.
[14] Brans 2005.

Chapter 7

The models of Hoyle, Bondi and Gold

Ce qui a été cru par tous
toujours et partout,
à toutes les chances d'être faux.

Tel Quel -Paul Valery-

In this chapter:

- A presentation of the steady-state model conceived by Bondi and Gold
- A study of the steady-state model conceived by Hoyle

This chapter presents the two versions of the Steady-State Theory introduced in 1948 namely by Bondi and Gold, and by Hoyle. This content has already been published[1].

One cannot study the steady-state cosmologies without considering two different approaches that are nowadays wrongly referenced collectively as the Bondi-Gold-Hoyle steady-state model. Hermann Bondi, Thomas Gold, and Fred Hoyle have spent a lot of time together during WWII and, according to Simon Mitton[2] and Mario Livio[3], the idea of an evolving but unchanging uni-

[1] Dubois and Füzfa 2019.
[2] Mitton 2011.
[3] Livio 2013.

verse pried into their mind after watching the film *Dead of Night*[4]. This leads these authors to two separate publications.

Indeed, in the fifth release of 1948 *Monthly Notices of the Royal Astronomical Society*, two papers can be found: *The Steady-State Theory of the expanding universe* by Bondi and Gold[5], submitted in July, followed by *A New model for the expanding universe* by Fred Hoyle[6], submitted in August. These two articles present crossed references and commentaries; however, the two expressed approaches are quite different epistemologically and mathematically.

First of all, it must be noticed that Bondi and Gold quote Hoyle's paper. As for him, Hoyle introduces his paper revealing how the general idea came from a discussion he had with Gold, and thanking Bondi for his comments and their many discussions. At first sight, one could wonder why they did not publish together. The reason is that, beyond their friendship, the ideas defended by the authors are, if not opposite, at least very different, and drive them to a kind of schism. In a later discussion[7], repeated below in a box, Hoyle is questioned by Schlegel about the Perfect Cosmological Principle, an idea developed by Bondi and Gold[8]; Hoyle's answer is welcomed by this self-explanatory comment by Bondi: "*We do not all agree*"[9].

Schlegel *I wish to ask Professor Hoyle: in introducing a perturbation in the C_i in some initial state, do you not lose the philosophical appeal of the steady-state theory of Professor Bondi's perfect cosmological principle?*

[4]Balcon 1945.
[5]Bondi and Gold 1948.
[6]Hoyle 1948.
[7]Hoyle and Narlikar 1962.
[8]Bondi and Gold 1948.
[9]Hoyle and Narlikar 1963, p.340.

Hoyle *It is a question of from what point of view you feel the aesthetic appeal. I feel that more in the equations. I feel that if I can see a set of equations where a small perturbation will make one go into a steady-state solution, I like that better. That to me is more aesthetic.*

Bondi *We do not all agree.*[a]

[a]Hoyle and Narlikar 1962, p.340.

This disagreement is also underlined several times by Helge Kragh[10,11]. The reading of these two articles as a unique Steady-State Theory conceived by these three authors is a mistake or, at least, late assimilation and a short-cut.

7.1 The Perfect Cosmological Principle

Hermann Bondi and Thomas Gold suggest a heuristic approach based on the *Perfect Cosmological Principle*. The Perfect Cosmological Principle shares the conviction of the universality principle according to which the laws of physics do not change with time and stay everywhere valid. Assuming this principle as correct leads Gold and Bondi to a universe that is homogeneous and steady at large scales.

As they note, the opposite hypothesis leads to an untenable situation. With this principle, one can be fully confident about the universality of observations and the validity of their interpretations. Considering a homogeneous and stable universe, one cannot reject the observed large-scale motions, so that the model must incorporate cosmic expansion. This development is illustrated by the three quotations in the following sidebar.

[10]Kragh 1999, pp.179-186.
[11]Kragh 2015a.

As the physical laws can not be assumed to be independent of the structure of the universe, and as conversely the structure of the universe depends on the physical laws, it follows that there may be a stable position[a].

We do not claim that this principle must be true, but we say that if it does not hold, one's choice of the variability of the physical laws becomes so wide that cosmology is no longer a science[b].
It is clear that an expanding universe can only be stationary if matter is continuously created within it[c].

[a]Bondi and Gold 1948, p.254.
[b]Ibid., p.255.
[c]Ibid., p.255.

Such an expanding universe can be *stationary*[12] only if you allow continuous creation of matter. Bondi and Gold then mention that such a model must be described by a de Sitter metric, as Einstein does in his draft in 1931 and as Hoyle does in his 1948 paper. Indeed, de Sitter's geometry incorporates cosmic expansion at a constant rate but requires a constant total density. Since matter density decreases due to cosmic expansion, this must be compensated by the continuous creation of matter. As mentioned by Einstein and de Sitter in 1932[13], only matter density and cosmic expansion rate were considered as observable at that time, therefore de Sitter's geometry was unavoidable to implement the Perfect Cosmological Principle.

Bondi and Gold then suggest some observational tests, even if they claim the creation process is too faint to be measured. They give an estimation of the rate of matter creation corresponding to the emergence of an atom of hydrogen per cubic meter per 3×10^5 years[14]. Bondi and Gold also consider the physical process of creation, but in a very qualitative way without a mathematical formulation.

[12]The choice of this term can be confusing as they consider a stationary universe and not a stationary space-time.
[13]Einstein and Sitter 1932.
[14]Bondi and Gold 1948, p.266.

General relativity demands that the laws of cosmology should be invariant while admitting that the one and only application is not invariant. We can see no reason why the laws of nature determining the structure of our universe should be invariant, although the universe is unique and does not bear an invariant aspect[a].

[a]Ibid., p.266.

Their model is not formulated within the context of general relativity, because Bondi and Gold question the assumption that general relativity is valid on cosmic scales, as the previous quote indicates. However, they note that the process of matter creation implies a privileged direction along the time dimension as described in Weyl's causal postulate. Hoyle implements this mathematically in his theory. Hermann Bondi and Thomas Gold are confident in the possibility of finding a mathematical formulation for their model in the context of field theory but they have a strong position against Hoyle's model (cf. the quotation in the next box). This rejection is especially due to the insertion of non-uniformities.

We have no hesitation in rejecting Hoyle's theory, although it is the first and at the moment only field theory formulation of the hypothesis of continuous creation of matter[a].

[a]Ibid., p.269.

This formulation of the Perfect Cosmological Principle could be considered as confusing. It seems that Bondi and Gold do not make the distinction between the physical laws and their solutions. It is now completely accepted that if equations are symmetric, the particular solution, resolving of a symmetry breaking, might not be. Bondi and Gold develop an essay without a formal mathematical model and it is something that could be desired by modern readers.

7.2 Mathematical approach to stationary cosmology

Born in 1915 in Yorkshire, Fred Hoyle keeps his popular accent during all his life. His father being absent because of the first World War, baby Fred accompanies his mother to her work as a cinema pianist. Fred's country-style education and his taste for truancy do not prevent him from studying in Cambridge.

In 1940, Hoyle is sent to Portsmouth to work on radars for the Admiralty. In this context, he meets Hermann Bondi and Thomas Gold with whom he spends a lot of time, even after the war. Their passionate conversations lead them to postulate the famous Steady-State Theory, in 1948.

Hoyle is concerned about the diffusion of knowledge. In 1950, during a famous series of emissions for the BBC, he dubbed the evolutionary cosmologies with the onomatopoeia Big Bang. Unfortunately, it turns out that the name remains, even if it has been suggested by an opponent. His outreach work is very popular and important. Stephen Hawking used to thank Hoyle for his vocation.

One of the dominant scientific achievements in Hoyle's career is the B^2FH paper, explaining in details stellar nucleosynthesis processes. For this amazing work, Fowler, one of the four signatories, receives the Nobel Prize in 1983. Even if Hoyle has been a few times anticipated as a Nobel laureate, his non-conventional research interests (Panspermia, deny of the archaeopteryx,..) and his really bad temper surely cost him this honour.

Be that as it may, he has an incredible career with wonderful international accomplishments. He is, for example, one of the initiators for the Anglo-Australian Telescope. Also, in 1967, Fred Hoyle is the founding director of the Institute of Astronomy (Cambridge).

After a career full of controversies, debates and conflicts, Hoyle signs his resignation in 1972 and definitely leaves his *Alma Mater*. He pursues his works till his dead in 2001 and always stays present in British hearts through his fictional works like *The Black Cloud*, *A for Andromeda* and the numerous books he writes with his son Geoffrey.

To pursue the discovery of this man of science, his autobiography is recommended[a]. There are also several testimonies from his collaborators and biographies.

[a] Hoyle 2015.

Hoyle, who was introduced above, bases his model[15] on the line of thought initiated by James Jeans[16] and Dirac[17], and develops the idea of continuous creation of matter for which Hoyle offers a mathematical formulation presented in the next box.

After a study of Newtonian universes, Hoyle turns to the framework of general relativity and, after some general considerations, works with the following line element[a]:

$$ds^2 = c^2 dt^2 - a^2(t) dl^2, \tag{7.2.1}$$

where $dl^2 = (dx^1)^2 + (dx^2)^2 + (dx^3)^2$ is the elementary length of flat Euclidean space with FLRW metrics. Following the standard procedure, Hoyle writes down the non-vanishing Christoffel symbols and components of the Ricci tensor, as well as the scalar curvature.

[a] In what follows, we have corrected some notations used by Hoyle.

Then Fred Hoyle chooses to "*diverge from the usual procedure*" by introducing a new mathematical term in Einstein's equations. From his conventional

[15] Hoyle 1948.
[16] Jeans 1928.
[17] Dirac 1937b.

metrics, he modifies cosmological equations. This term describes the process of continuous matter creation. Hoyle's formalism is expounded in the next insert.

Hoyle adds a space-time four-vector field C_μ whose norm is defined by its parametrisation in the co-moving referential along the time-like geodesics:

$$C_\mu = 3\aleph(1,0,0,0), \tag{7.2.2}$$

where $\aleph$ is a constant. This vector C_μ has vanishing spatial components for symmetry reasons and compatibility with the chosen metric. Then, Hoyle constructs a symmetrical tensor $C_{\mu\nu}$ by covariant differentiation of the four-vector field,

$$C_{\mu\nu} = \nabla_\nu C_\mu\cdot \tag{7.2.3}$$

Given the above-mentioned symmetries, this "*creation*" tensor $C_{\mu\nu}$ counts only three non-zero components:

$$C_{ii} = -3\frac{\aleph}{c}a\dot{a}\ ;\ i = 1,2,3\cdot \tag{7.2.4}$$

Hoyle then introduces the following *modification* of the Einstein field equations:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + C_{\mu\nu} = -\kappa T_{\mu\nu}\cdot \tag{7.2.5}$$

Doing this, the stress-energy tensor $T_{\mu\nu}$ is no more longer conserved. Indeed, from the second Bianchi identity, we have:

$$\nabla_\mu\left(R^{\mu\nu} - \frac{1}{2}g^{\mu\nu}R\right) = 0.$$

Then we find that the creation tensor is the source of the production of new particles:

$$\nabla_\mu T^{\mu\nu} = -\frac{1}{\kappa}\nabla_\mu C^{\mu\nu} = -\frac{1}{\kappa} g^{\alpha\nu}\nabla_\mu\nabla_\alpha C^\mu. \tag{7.2.6}$$

One can see that, if $\aleph = 0$, we find back an Einstein-de Sitter universe for a pressure-less matter universe with varying ρ, while, here, ρ is constant. As $\nabla_\mu T^{\mu\nu} \neq 0$, the stress-energy tensor is not conserved and the matter geodesics will be modified, C_μ acting like a long-ranged force.

Therefore, in Hoyle's theory, one expects the free fall of matter particles to be affected by this new long-ranged force on cosmological distances. Exploring the observable constraints of this phenomenological property would be a significant and interesting work.

About Einstein's 1931 draft and Hoyle's model, one can notice a similarity between the cosmological constant term and the creation tensor. In 1951, McCrea[18] includes the creation tensor $C_{\mu\nu}$ directly into the total stress-energy tensor on the right-hand side of Einstein equations, so that their form stayed unchanged. Thereby, he rightly claims there is no net creation of matter since the total stress-energy tensor is conserved, due to the second Bianchi identity. However, this yields some coupling between usual matter and its source, given by $C_{\mu\nu}$, and so there is indeed no conservation of the number of usual matter particles.

It is important to notice that Hoyle puts the term $C^{\mu\nu}$, responsible for the creation of matter, on the left-hand side of his modified Einstein equations, as a modification of the geometry in the field equations. This approach is similar to Einstein's one in 1917, with his introduction of the cosmological constant term, with the important difference that the modification brought by Hoyle does have an impact on matter conservation while this is not the case for the cosmological constant term. Matter conservation laws are the same whatever the value of the cosmological constant, while matter conservation laws must include the creation term in Hoyle's approach. Yet both approaches by Einstein in 1917 and Hoyle in 1948 consist of modifying the way space-time is curved

[18] McCrea 1951.

by matter to account for cosmological considerations.

Besides, Hoyle's model allows matter creation without introducing any violation of the fundamental laws of covariance and the equivalence principle. Gravity is still described through only one metric in the Levi-Civita connection so that the total stress-energy and Einstein's tensors are conserved. Matter creation can be seen as the result of some interaction between usual matter and some invisible sector through the term $C_{\mu\nu}$. In Hoyle version of the Steady-State Theory[19], this sector is modelled in cosmology by some frozen vector field Eq.(7.2.2).

In the metric chosen by Hoyle, the modified Einstein field equations become (temporal equation first, then the spatial one):

$$3\dot{a}^2 = \kappa\rho c^4 a^2 \cdot \tag{7.2.7}$$

$$2a\ddot{a} + \dot{a}^2 - 3\aleph c a\dot{a} \quad = \quad 0 \tag{7.2.8}$$

It is possible to show that this set of equations has a first integral that takes the form of a Bernouilli equation. The general solution is

$$a(t) = \left(C_1 + C_2 e^{\frac{3}{2}\aleph ct}\right)^{\frac{2}{3}} \tag{7.2.9}$$

The particular solution given by Hoyle, supposing $\dfrac{\dot{a}}{a} = \aleph c$ at $t = 0$, is

$$\begin{cases} \frac{3}{4}\aleph ct = \tanh^{-1}\left(\frac{2\dot{a}}{a\aleph c} - 1\right) - \tanh^{-1}\left(2\alpha - 1\right), \text{ if } \alpha < 1, \\ \frac{3}{4}\aleph ct = \coth^{-1}\left(\frac{2\dot{a}}{a\aleph c} - 1\right) - \coth^{-1}\left(2\alpha - 1\right), \text{ if } \alpha > 1. \end{cases} \tag{7.2.10}$$

Isolating $\frac{\dot{a}}{a} = d(\log(a))/dt$ in (7.2.10), it becomes easy to develop these expressions to have the general solution. For the first equation of (7.2.10), $-\dfrac{a}{c}C_1 = \dfrac{1}{2}e^{\frac{3}{2}D - C}$ and $-\dfrac{3c}{a}C_2 = \dfrac{1}{2}e^{\frac{3}{2}D + C}$ where $C = \tanh^{-1}(2\alpha - 1)$ and D is an integration constant.

[19] Hoyle 1948.

It is interesting to notice that the general solution (7.2.9) of Hoyle's model only reduces to de Sitter space-time and a constant Hubble parameter for this particular choice of initial conditions Eq.(7.2.10) (or $C_1 = 0$ in (7.2.9)) or, equivalently, $a \to 0$ if $t \to -\infty$. This is the only choice allowing both constant density and Hubble parameter, since if $a \to a_{-\infty} \neq 0$ when $t \to -\infty$, one finds a solution with varying density and Hubble parameter.

Hoyle's steady-state cosmological model (expounded in the previous sidebar) is, therefore, a consequence of a modification of the cosmical ingredients, as it can be done with dark matter or dark energy, and a particular choice of initial conditions to guarantee the constancy of H_0 as was considered by many at that time.

Hoyle comes to this conclusion: "*It is only through the creation of matter that an expanding universe can be consistent with conservation of mass within the observable universe*"[20]. In standard cosmology, based on general relativity, it is the stress-energy tensor that is conserved through the conservation laws $\nabla_\mu T^{\mu\nu} = 0$. Hoyle instead requires that it is the *mass* that is conserved all along with cosmic expansion, which is very different: mass is a global quantity[21] while stress-energy is a local one. To ensure this conservation of mass during cosmic expansion, Hoyle has modified Einstein's general relativity but in such a way that there are still conservation laws, but only for the total stress-energy tensor $T_{\mu\nu} + \frac{1}{\kappa} C_{\mu\nu}$. Also, the matter creation process must exactly balance the decrease of matter density due to the cosmic expansion, which imposes some symmetries to the vector field C_μ.

McCrea[22] suggests that a satisfactory description of the consequences of the creation hypothesis may, nevertheless, be obtained without any modification of Einstein's equations. The creation tensor $C_{\mu\nu}$ is absorbed in the stress-energy tensor.

Hoyle's model has an infinite past and an infinite future, it also satisfies the Wide (or, in Bondi and Gold's wording, the Perfect) Cosmological Principle.

[20] Hoyle 1948, p.379.
[21] Blanchet, Spallicci, and Whiting 2011.
[22] McCrea 1951.

However, this is a consequence in Hoyle's development when it is the starting hypothesis of the Bondi-Gold model. Hoyle's steady-state model emerges from an extension of general relativity and matter content that still incorporates conservation laws but with an extended definition of the matter content of the universe. Therefore, Hoyle's approach is also reminiscent of the one made by Einstein in 1917, when the father of general relativity introduced his famous cosmological constant.

It is interesting to notice the similarity, at first sight, of Hoyle's and Jordan's models. Max Born had even invited Jordan to express himself on Hoyle's steady-state model[23]. One of Hoyle's motivation is the refusal of a beginning of time, which could be taken for biblical creation. However, under the guise of positivism, one motivation of the Christian Jordan is to react to materialism. It is curious to note that such opposite motivations lead to the same product, namely the creation of matter.

[23] Jordan 1949.

Part III

Second half of the twentieth century

Chapter 8

Cosmological observations and steady-state universe

Those of us who are not directly involved in the fray can only suppose that the universe is open on Wednesday, Friday and Sunday and closed on Thursday, Saturday and Monday. (Tuesdays is choir practice.)

Contemporary Physics -Virginia Trimble-

In this chapter:

- A development of the Steady-State Theory
- A presentation of sixties new cosmological observations
- An analysis of their interpretation in the Steady-State Theory

8.1 The Steady-State Theory in the sixties

At the beginning of the sixties, Hoyle has reunited quite a team around him, notably Jayant Narlikar and Chandra Wickramasinghe. Both have first been his Ph.D. students and then become his close collaborators. Since 1948, they have worked on the Steady-State Theory and its development. In 1965, Hoyle and Narlikar sign jointly two important articles bringing mathematical reasoning in favour of a revision of their theory.

The first publication[1] broaches the link between the massive objects, of cosmological significance, and the problem of creation in cosmology. It seems to them that the cosmologies with a singular origin are inconsistent with the law of baryon conservation; while oscillating models, although not satisfactorily described yet, could be consistent with this conservation law.

From the conservative point of view, particle physics is more definitive than cosmology and the baryons are conserved. The mathematical difficulties of the oscillating model of the universe will eventually be overcome. From the less-conservative point of view, the law of baryon conservation is given up in strong gravitational fields. And cosmology has to deal with strong fields. By accepting the possibility of non-conservation of baryons, cosmology requires the C-field, introduced previously by Hoyle[2]. The next sidebar shows the properties of the C-field as listed by Hoyle. Then, a technical box expounds the mathematical apparatus of this model.

Some properties of the C field are listed.

- *C field arises whenever a baryon (and its accompanying lepton) is created or destroyed. It is linked to the extremities (beginning and end) of world-lines.*
- *C field does not affect the world-line of a particle during its existence, only its ends. It determines the condition of creation or destruction at any point in space-time.*
- *C field affects space-time through stress-energy tensor in Einstein's equations. It has a negative energy density.*[a]

[a] Hoyle and Narlikar 1966c, *C-field Physics - a Brief Résumé.*

[1] Hoyle and Narlikar 1966c.
[2] Hoyle 1948.

The C field originating from the particle world-line a, beginning or ending at A, at a point X is $C^{(a)}(X) = -\left(\frac{\epsilon}{f}\right)\overline{G}(A, X)$ where $\overline{G}(A, X)$ is a two-point scalar Green function. $\epsilon = +1$ means a creation at A while $\epsilon = -1$ translate a destruction at A. f is a coupling constant. At a point X, the total C field is defined by the addition of all contributions $C(X) = \sum_a C^{(a)}(X)$. It also solves the wave equation $C^{\lambda}_{;\lambda} = \frac{n}{f}$, with n the number of pairs created per unit of volume and time.

At X, $C^k C_k = E^2$, a pair of baryon-lepton of total energy E may be created, with the momentum $p_\mu = C_\mu$ at X. Creation of more than one pair can be considered under the generalised condition $p_\mu^{(1)} + p_\mu^{(2)} + ... = C_\mu$

The energy-momentum tensor of the C fields arising from baryons a, b is given by

$$H^{(a,b)}_{\mu\nu} = -f\left[C^{(a)}_\mu C^{(b)}_\nu + C^{(b)}_\mu C^{(a)}_\nu - g_{\mu\nu} C^{(a)}_\lambda C^{(b)\lambda}\right].$$

The total contribution, from all pairs (a, b), is $H_{\mu\nu} = \sum_a \sum_b H^{(a,b)}_{\mu\nu}$. With a large enough number of particles, this tensor can be approximated by $H_{\mu\nu} = -f\left[C_\mu C_\nu - \frac{1}{2} g_{\mu\nu} C_\lambda C^\lambda\right]$.

Einstein equations are modified

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G\left[T_{\mu\nu} - f\left(C_\mu C_\nu - \frac{1}{2} C_\lambda C^\lambda\right)\right]$$

Hoyle and Narlikar study the possible cosmological oscillating model with homogeneity and isotropy. When the scale factor, denoted by $a(t)$ in FLRW metric, reaches a maximal value, the universe begins a contraction phase. And when it reaches a minimal value, the universe goes back into an expansion phase.

Since Narlikar's doctorate, both Hoyle and Narlikar are in a reflection about time and its interpretation[3]. They suggest an infinite universe built on symmetrical time, as illustrated in following sidebar.

When the time is infinite in the past, a new temporal coordinate can be studied $T' = -T$.

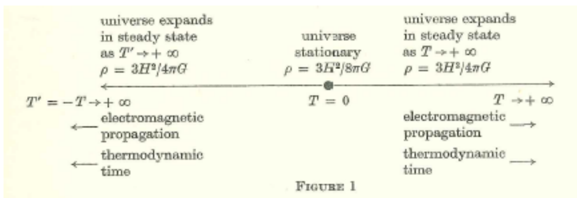

Illustration of time arrow in oscillating model Hoyle and Narlikar 1966c, p.148.

Hoyle and Narlikar also consider the consequences of non-homogeneities. The mass concentrations become pockets of creation. By doing so, they can link the expansion of the universe to the inhomogeneities in mass distribution. This leads them to bind cosmology and astrophysics, this being the wonderful advantage of their model.

They also discuss some issues of their model, by focusing on the main one, the creation/destruction problem that can be seen in analogy with electrostatic,as illustrate by the quotation in the box below. The creation conveys a positive field while the destruction is the result of a negative field. The idea of thermodynamical equilibrium means that the two processes balance each other. However, one is entitled to wonder if this is what they meant.

[3]Hoyle and Narlikar 1964c.

However, just as in the electromagnetic case a thermodynamic equilibrium is not reached between matter and radiation in the universe, in the present case we similarly think that creation predominates over destruction in the cosmological situation. Indeed, so long as there is no strict detailed balancing, we can always choose the sense of our time axis so that there is a preponderance of 'creation[a].

[a]Hoyle and Narlikar 1966c, p.154.

In the aftermath of this work, Hoyle and Narlikar submit an article with an evocative title *A radical departure from the 'steady-state' concept in cosmology*[4]. Even though they previously chose to make the steady-state expansion rate coincident with the observed expansion rate, now they prefer a much greater value. The difference is that the observable universe is in a wide, possibly temporary, fluctuation from the steady-state situation. This committed stance permits to deeply link astrophysical results and cosmology. The next sidebar introduces a technical concept to understand the following quotation.

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G \left[T_{\mu\nu} - f \left(C_\mu C_\nu - \frac{1}{2} C_\lambda C^\lambda \right) \right]$$

In the homogeneous isotropic case, only $\dot{C} = m_0$ is not null. The creation is uniform and everywhere at a rate $3Hfm_0^2$.
In the theory of pocket creation, there is a threshold m_0^2 for creation, a massive object, with strong enough gravitational field to raise $C_\mu C^\mu = m^2$ is required.

[4]Hoyle and Narlikar 1966b.

Short of abandoning the whole theory, it is necessary either

1. *to drop the idea that the origin of cosmic rays and high energy electrons is connected with the creation process, or*

2. *to increase the coupling constant* f *[the coupling constant] by a very large factor, of the order* 10^{20}.

In the first case the attractive features discussed in the preceding section [Creation of energetic particles] are lost. The theory remains much the same as it was before – that is to say, the cosmological aspects of the theory survive as set out in I[a]. *Creation of matter is then confined to galaxies and clusters of galaxies and is at a gentle rate.*

If the second possibility is considered, f *will have to be increased. This means* $\dot{C}$ *must be reduced by* $\sim 10^{-10}$ *in order to maintain* $f\dot{C}^2$ *at the same cosmological value as before. Thus* m *is reduced by* $\sim 10^{-10}$ *and the requirement* $m_0 \simeq m$ *can no longer be maintained. In other words the work described in I is lost.*

[...]

Clearly then, we must follow the second possibility, even though this means throwing overboard the usual framework of the steady-state theory[b].

[a] Hoyle and Narlikar 1966c.
[b] Hoyle and Narlikar 1966b, pp.168-169.

Thereby, in the middle of the sixties, the supporters of the Steady-State Theory make a breakthrough and completely change their point of view on their model. This is not the only change of great importance at this time. Some wonderful and important observations are on the verge of being made.

8.2 Cosmological observations

The sixties have seen some wonderful advances in the field of cosmology. Three breakthroughs are presented in this section. First, the journey from the prediction to the observation of the Cosmological Microwave Background is tackled. Second, the Quasi-Stellar objects are displayed, from their first detection to their modern interpretation. Last, and important for the purpose of this thesis, the characteristics of the interstellar medium are introduced.

8.2.1 Cosmological Microwave Background

In 1948, George Gamow and his collaborators study the potential observational consequences of Lemaître's cosmological model. Gamow predicts the possibility of the Big Bang nucleosynthesis, i.e the formation of light elements in the primordial universe[5]. He has also the intuition of remainder radiations of those early times[6]. Quickly, Gamow's colleagues notice some miscalculations and refine Gamow's prediction[7]. Their correction is repeated in the following sidebar. From original, and miscalculated Gamow's prediction of a radiation of $340K$[8], Alpher and Hermann put a much better prediction forward[9]. The estimated radiation, about $5K$, is the first accurate prediction of what will be called the Cosmic Microwave Background.

The temperature of the gas at the time of condensation was $600^\circ K.$*, and the temperature in the universe at the present time is found to be about* $5^\circ K$[a].

[a] Alpher and Herman 1948, p.775.

Strangely, their prediction had almost no impact. This could be attributed to Gamow's bad renown. In 1965, everything is upside down. Two engineers, working for Bell Telephone Laboratories, detect radiations of unknown origin. A team of physicists interpret this radiation as what they are looking for. This leads to a double publication in Astrophysical Journal.

First, Dicke, Peebles, Roll, and Wilkinson sign an article entitled *Cosmic Black-Body Radiation*[10]. In their point of view, there are only three possible answers to cosmological problems (i.e the singularity characteristic of the cosmological solution, the excess of matter over anti-matter, the origin of matter, and the genesis of the universe). On the second hand, like in Hoyle's work, a continuous creation can be considered. This cosmological model predicts a universe expanding at all times and a continuous, but slow, creation of new matter. On the other hand, following Wheeler, the resolution of cosmical problems may be found in a proper quantum mechanical treatment of Einstein's

[5] Gamow 1946.
[6] Gamow 1948.
[7] Alpher and Herman 1948.
[8] Gamow 1948.
[9] Alpher and Herman 1949.
[10] Dicke et al. 1965.

field equations. On the other hand, the third option is to consider the primordial singularity like the consequence of a mathematical over-idealization: the isotropy and the uniformity do not apply to the real world.

Considering closed oscillating models and a universe with singular origin leads to an extremely hot universe in its early stages. By acknowledging an expanding universe filled with black body radiation, they have to examine the cooling of this radiation. The temperature of the radiation must vary inversely as the radius of the universe. The goal is to measure this cooled radiation, as it is expressed in the following excerpt.

Evidently, it would be of considerable interest to attempt to detect this primeval thermal radiation directly. Two of us (P.G. Roll and D.T. Wilkinson) have constructed a radiometer and receiving horn capable of an absolute measure of thermal radiation at a wavelength of 3 cm. The choice of wavelength was dictated by two considerations, that at much shorter wavelengths atmospheric absorption would be troublesome, while at longer wavelengths galactic and extragalactic emission would be appreciable[a]*.*

[a]Dicke et al. 1965, p.415.

Their experiments have no conclusive result. However, knowing Penzias and Wilson's observations, detailed below, Dicke, Peebles and collaborators interpret them as the radiation they were looking for[11]. Penzias and Wilson observe background radiations of 7.3cm or 3.5°K. An excerpt of this famous publication is repeated here.

While we have not yet obtained results with our instrument, we recently learned that Penzias and Wilson (1965) of the Bell Telephone Laboratories have observed background radiation at 7.3 cm wavelength.

[11]It should be noted that Dicke, Peebles and their collaborators reconstructed the reasoning leading to the prediction of the CMB radiation. They worked in total ignorance of Alpher and Herman's previous results (Kragh 1999).

> *In attempting to eliminate (or account for) every contribution to the noise seen at the output receiver, they ended with a residual of* $3.5° \pm 1° K$. *Apparently this could only be due to radiation of unknown origin entering the antenna.*
> [...]
> *A temperature in excess of* $10^{10°} K$ *during the highly contracted phase of the universe is strongly implied by a present temperature of* $3.5° K$ *for black-body radiation*[a].
>
> [a]Dicke et al. 1965, p.416.

They notice that the black body radiation measured is isotropic and uniform. This tends toward a universe old of 10^{10} years in which Einstein's equations are valid. The observation seems also to favour an open universe, rather than a closed one[12].

Second, Penzias and Wilson publish a short paper under the title *A Measurement of excess antenna temperature at* $4080 Mc/s$[13,14]. Penzias and Wilson only share their observation of an excess temperature. They can add some characteristics of their measures, it is isotropic, unpolarized, and free from seasonal variation (as their measurements took place from July 1964 to April 1965). They leave the physical interpretation of their discovery to qualified scientists, especially the previously mentioned team.

The supposedly isotropic radiation has been deeply studied, among others, by spatial missions: COBE (1989-1993)[15], WMAP (2001-2010), and PLANCK (2009-2013). Nowadays, the radiation is called the Cosmological Microwave Background. It is interpreted as the primordial radiation corresponding to the decorrelation of light and matter, roughly the formation of neutral atoms out of ionised gas. If Big Bang occurred, this first light was emitted when the universe was, approximately, 380000 years. Its tiny anisotropies are studied to collect information on the structure, the evolution, and the composition of the universe.

[12]Dicke et al. 1965, p.418.

[13]Here, c is not the speed of light but the abbreviation of cycle. A cycle is equivalent to the Hertz.

[14]Penzias and Wilson 1965.

[15]The 90's renewed interest for the this observation and its consequence for the Steady-State Theory is presented in Chapter 10.

8.2.2 Quasi-Stellar Objects

After World War II, the radars and other instruments found a new application . By turning the radars at the sky, physicists create a new scientific field: radio-astronomy.

John Bolton's team brings to light that some radio sources have stellar characteristics, and he calls them *radio stars*. In 1948, they study some radio sources with no associated visible object, as illustrated by the following box. They announce also the discovery of radio stars out of our galaxy[16].

As in the case of Cygnus, the new sources do not appear to be associated with outstanding stellar objects.
[...]
A contribution from individual discrete sources, which may be distinct 'radio-types' and for which a place might have to be found in the sequence of stellar evolution[a].

[a]Bolton 1948, p.142.

During the 1950's, A. Hewish, M. Ryle and F. Graham-Smith list those new objects in the *Third Cambridge Catalogue of Radio Sources*. The object listed as 3C273 is the most luminous. Progressively the term Quasi-Stellar Objects tends to evince the radio-stars. In 1962, the redshift of 3C48 is measured[17]. The designation *quasar* is first used by Hoong-Yee Chiu in 1964 (cf. the following sidebar).

[16]Bolton, Stanley, and Slee 1949.
[17]Greenstein and Mattews 1963.

So far, the clumsily long name "quasi-stellar radio sources" is used to describe these objects. Because the nature of these objects is entirely unknown, it is hard to prepare a short, appropriate nomenclature for them so that their essential properties are obvious from their name. For convenience, the abbreviated form "quasar" will be used throughout this paper[a].

[a] Chiu 1964, p.21.

Changing the name of the object and clarifying the concept are not enough to capture all the complexity of those celestial bodies. They can be divided into two categories, according to their radiation, there are the radio-loud and the radio-quiet quasars. The problem of determining their distance is total, in the sixties. Gamow took this situation with some humour and spoofed a famous nursery rhyme, this is given in the next box. Either they are remote and their distance can be estimated through their redshift, or they are close and their redshift can be explained by the evasion of light from a deep gravitational well, the so-called Einstein effect or gravitational redshift.

Twinkle, twinkle quasi-star
Biggest puzzle from afar
How unlike the other ones
Brighter than a billion suns
Twinkle, twinkle, quasi-star
How I wonder what you are[a].

[a] Gamow 1964, from the nursery rhyme.

From the 1980s, the quasars are better understood and belong to the family of Active Galactic Nuclei (AGN). Quasars are a type of AGN just like radio-galaxies or blazars, blazing quasi-stellar radio sources.

8.2.3 Impurities in interstellar grains

The interstellar medium, i.e. the matter and the radiation existing in space, between stars, has been studied since the beginning of the twentieth century. In 1904, studying the spectrum of the star *δ Orionis*, J. Hartammn brings to light the particular behaviour of the calcium line 3934Å[18]. This observation leads him to consider a cloud of calcium vapour in the interstellar medium. Mary Lea Heger follows the lead and, in 1919, shares her detection of interstellar sodium[19].

The study of interstellar gas and dust continues and, in the sixties, there are pieces of evidence in favour of the existence of so-called interstellar grains. Those are graphite nuclei (of the order of ten nanometres) coated with an ice mantel. It is most likely that some impurities, like foreign atoms, are embedded into the grains, in their crystal structure[20].

8.3 Observations in the Steady-State Theory

Those observations have to be incorporated into the scientific theories of the epoch. The case of the Cosmic Microwave Background is particular. On the one hand, the CMB has been predicted by the supporters of the Big Bang model and fits perfectly in the theory. On the other hand, the Steady-State Theory has to account for this observation. The same reasoning applies to the Quasi-Stellar Objects, a place for them has to be found in the theoretical developments. This section is devoted to explaining how the steady-state supporters incorporate the previous expounded observations in their model.

Before proceeding, another important observation deserves to be mentioned. As explained before, Hubble's law of expansion of the universe can be linked to its age. Unfortunately, Hubble's data gave an age for the universe more little than the age of the stars, or even the Earth. This fact was an exceptional motivation for Hoyle and his collaborators to deny this interpretation of Hubble's law. However, over the years, observations became more precise and the first rough approximation oh Hubble's constant refined. Researches as such as the one of William Baade or Allan Sandage permit to establish a constant coherent met the geophysical observation of the age of the other celestial objects[21]. This is illustrated by the next quotation box. One of the main argument in favour of

[18] Hartmann 1904.
[19] Heger 1919.
[20] Hoyle and Wickramasinghe 1962.
[21] Sandage 1958.

Steady State Theory fall apart. This last model needed to evolve and convince again.

> *The major conclusion is that there is no reason to discard exploding world models on the evidence of inadequate time scale alone, because the possible values of H are within the necessary range.*[a]
>
> [a]Ibid., p.525.

8.3.1 QSO and redshift

In 1966, Fred Hoyle, in collaboration with George Burbidge, dedicate some of his time to the study of the Quasi-Stellar Objects. First, they present in detail their interpretation of what is a QSO[22]. If the commonly accepted interpretation puts the QSOs at cosmological distances (between 100 and $1000Mpc$[23]), Hoyle and Burbidge consider the possibility to put them in a more local environment, between 1 and $10Mpc$.

The cosmological location of QSOs has, then, three likely explanations. Either QSOs are galaxies pictured during their process of formation; or QSOs, as well as some nuclei of galaxies, are relics of a high density phase of the whole universe; or QSOs are the final products of star collisions. In Hoyle's point of view, QSOs are ejected compact objects. They can be ejected from our galaxy or from a powerful radio galaxy, in the neighbourhood of the Milky Way. Hoyle and Burbidge are in favour of QSOs located about $10Mpc$ away from us and suggest some observational programs to confirm their idea.

Quickly after this publication, Fred Hoyle, Geoffrey Burbidge, and Wallace Sargent publish an additional argument[24]. They explore the physical processes which could explain the radiation emitted by the QSOs. Their results seem to confirm a local position (cf. the following quotation).

[22]Hoyle and Burbidge 1966a.

[23]The parsec (pc) is an astronomical length measure corresponding to the distance from the Sun to observe the interval between Sun and Earth with an angle of $1°$. 1pc is equivalent to 3.26 light-year.

[24]Hoyle, Burbidge, and Sargent 1966.

We conclude that either the quasi-stellar objects are at distances of $\sim 10Mpc$ *or less, or the physical model associated with these objects must be substantially different from the theories at present in vogue*[a].

[a]Hoyle, Burbidge, and Sargent 1966, p.753.

A third paper has to be underlined in which Hoyle and Burbidge study some properties of the QSOs[25]. First, they denote S the flux density of a source and count the number of sources with an equal or bigger flux density than fixed S, $N(S)$. This approached is explained in the next insert.

They focus on 30 objects. As 30 is equal to $2+2^2+2^3+2^4$, Hoyle and Burbidge define S_1, S_2, S_3 and S_4 such that $N(S_1) = 2$, $N(S_2) = 6$, $N(S_3) = 14$ and $N(S_4) = 30$. By plotting those points in a $\log N - \log S$ plane, they find a slope close to -1.5. From this little sample of QSOs, they can deduce the relation $NS^{3/2} \approx constant$.

They compute the famous relation $\log(N)$-$\log(S)$ [26]. The slope of their graph is about -1.5, which is far different from the -1.85 obtained for all the radio sources and from the -2.2 computed by Veron for the QSOs from the 3C catalogue[27]. It is to highlight that those results spelt the end of Steady State Theory for many scientists. The prediction of -1.5 was too distant from the accurate observations of a slope of -2.2. From that moment, the supporters of the Steady State Theory were only in a defensive position.

Then, Hoyle and Burbidge address the issue of the QSOs redshifts. It seems that, by accepting the cosmological interpretation of the redshift, the smaller

[25]Hoyle and Burbidge 1966b.

[26]A controversy about the correct slope of this graph will polarize the community between Hoyle's results and Martyn Ryle's ones. Ryle, by drawing on his results, assures that he rules out the Steady-State Theory (Ryle and Clarke 1961).

[27]Veron 1966.

is S, the bigger must be the redshift. However, their graph does not show any relation of this kind, which leads them to deny any distance interpretation of the redshift, as evidenced by the following quote.

> *If we make the assumption that the red-shifts z of the quasi-stellar spectra arise from the cosmological expansion of the universe, then small S must be correlated with large z. In Fig 2 (red-shift versus radio magnitude for quasi-stellar objects it is shown emphatically that this is not so. Thus if we adopt the usual distance-volume interpretation of the result $NS^{3/2} \approx constant$, we must conclude that the red-shifts have nothing to do with distances*[a].
>
> [a]Hoyle and Burbidge 1966b, p.1346.

8.3.2 Impurities and CMB

Hoyle and Wickramasinghe study the properties of the interstellar medium and their impurities[28]. As the central graphite of the grain is originally expelled in HII regions from the star atmosphere, there is a non-null probability of collision. Those chaotic environments provide enough matter and speed to change the collisions into penetration and merging. Gradually, the graphite nucleus covers itself with an ice mantel. During the mantel growth, impurities may be covered and embedded as well as the graphite. This one-way process leads to a certain number of foreign atoms to be incorporated into the grains. This comes directly from the excerpt below.

> *Because of the general one-way character of the process it is reasonable to suppose that grains acquire a considerable number of impurity atoms over the course of their lifetimes, $\sim 10^9$ years.*

[28]Hoyle and Wickramasinghe 1967.

> *Of the order of* $\sim 10^3 - 10^5$ *such atoms per grain an have important effects on the interaction of grains with radiation, over the whole waveband ranging from the visible to the far infra-red. The requirement is for one foreign atom to* $\sim 10^3 - 10^5$ *atoms of the host crystal, a proportion that seems reasonable*[a].
>
> [a]Hoyle and Wickramasinghe 1967, p.970.

The impurities bring long wave oscillators in the grains. They make effective the conversion of radiation at an optical frequency to far infra-red. The thermalization induced by the grains provides uniform radiation at $3°K$. Then, the dust thermalization permits a logical explanation of the observations aforementioned; a better explanation, according to them, than the CMB interpretation.

Four months after Hoyle's explanation, Narlikar, and Wickramasinghe summarise the interpretation and explanation of the microwave background in a steady-state universe[29]. The radiation observed by Penzias and Wilson[30] can be interpreted as a relic of a radiation early phase of the universe, but they prefer to explain it by a far more local origin. The energy arising from the conversion of hydrogen to helium is thermalized by dust grains and re-emitted at the observed temperature. This explanation has the advantage of linking the measured flux with processes occurring locally.

Narlikar and Wickramasinghe continue their research in the following months[31]. The process they defend explains and clarifies the production of microwave radiation. The impurity oscillators in the interstellar dust grains absorb optical and ultraviolet radiation from stars and re-radiate at longer wavelengths. The article is also mean to expound some important differences between Big Bang cosmology and the Steady-State Theory. Regarding the redshifts, SST permits them to be infinite; while, in Big Bang theory, the upper limit of redshift is set by the epoch of the galaxy formation. Besides, evolutionary cosmologies tolerate the use of arbitrary epoch-dependent functions, when this freedom is denied for the Steady-State Theory. It is also the moment for the authors to declare that neither the observation of the QSOs nor the detection of a microwave background rules out their model, as it can be read in the following quotation.

[29]Narlikar and Wickramasinghe 1967.
[30]Penzias and Wilson 1965.
[31]Narlikar and Wickramasinghe 1968.

For this reason, it is also premature to conclude from the present observations that the Steady-State Theory of the universe is untenable[a].

[a]Ibid., p.1236.

In this series of publications, a fourth one can also be quoted. Hoyle, Wickramasinghe and Narlikar link strongly the microwave background and galactic processes[32].

[32]Hoyle, Wickramasinghe, and Reddish 1968.

Chapter 9

Dirac in the seventies

Bien que nous parlions tant de coïncidences, nous n'y croyons pas vraiment. Au fond de nous-mêmes, nous avons une meilleure idée de l'Univers, nous sommes secrètement convaincus qu'il n'est pas une affaire baclée ou due au hasard mais que tout en lui a une signification.

-John Priestley-

In this chapter:

- A revival of Dirac's cosmological model
- A study of its consequences and interpretations

After his attempted model based on the Large Numbers hypothesis, Dirac does not seem interested in the further development of cosmology. Nevertheless, in the 70s, Dirac comes back to his model and rephrases it. He explores the diverse matter creation scenarios and tries to integrate the microwave background in his cosmology. Dirac publishes some articles about this model[1,2,3]. Moreover, in a series of public lectures in New Zealand in 1975, Dirac broaches this subject[4]. This chapter explores the restyled Large Numbers hypothesis cosmology.

[1] Dirac 1973a.
[2] Dirac 1974.
[3] Dirac 1979.
[4] Dirac 1975.

9.1 Motivations

Assuming the Large Numbers hypothesis according to which the dimensionless large numbers occurring in the modelling of the world should be seen as functions of the epoch, the age of the universe expressed in atomic units, Dirac builds a cosmological model. There are two different approaches to cosmology, that have been previously mentioned in this piece of work. On the one hand, the universe could be thought of in a steady state. The universe has always existed and has always been similar to what it is now. Or, on the other hand, the universe is considered evolutionary. In the standard picture, the universe has a beginning at a definite time and is always changing. The Large Numbers hypothesis demands an evolutionary cosmology, in which G is decreasing forever and the whole picture of the universe departs more and more from its first configuration.

9.2 Law of expansion

A cosmological model must be coherent with observations and experimental data. Dirac's model[5] has no exemption from the rule and must take into account the recession of galaxies interpreted as an expansion of the universe. However, the models, in which the universe is expanding to a maximum size and then contracting, must be excluded. Indeed, the maximum size, in any value, could be expressed in units to become a dimensionless large number, independent of the epoch. This is a clear contradiction of the fundamental principle of the Large Numbers hypothesis. The previous reasoning is technically presented in the next insert.

Considering the distance between two galaxies, it could be written $p\,a(t)$, where p depends on the pair chosen, and $a(t)$ is the law of expansion of the universe, identical for each pair of galaxies, if the universe is uniform.

[5] Dirac 1973a.

According to Dirac, the expansion law can have two different forms, $a(t) = t^n$ or $a(t) = \ln(t)$, and so the velocity of recession is $cst\,n\,t^{n-1}$ or $\frac{cst}{t}$.
$n > 1$ translates an accelerating expansion,
$n = 1$ corresponds to a uniform expansion,
$n < 1$ or the logarithmic expression is a model of the decelerating expansion.

The present case must be decided from observational data. A nearby galaxy has been observed with a velocity of recession close to 10^{-3}. The hypothesis $n > 1$, translating the steady increasing velocity, can not be allowed. In the case $n < 1$, the velocity decreases so at a time t_1 of the past, the velocity was equal to 1. When n is little, t_1 is large and contradicts the Large Numbers hypothesis. The simplest case occurs when $n = 1$ or slightly less than 1.

9.3 Creation of matter

Applying the Large Numbers hypothesis to the dimensionless numbers built from the mass of the universe compared to the mass of a nucleon, the amount of matter in the universe must continually increase. Dirac's cosmology is a model with a continuous creation of matter. Either the matter is created uniformly throughout space, what Dirac calls the additive creation, or the matter is created in proportion to the amount of existing matter, in its inhomogeneity,what is named the multiplicative creation[6].

Dirac develops a cosmological model without any wish to abandon Einstein's general relativity, in which G is constant. The problem is to modify the theory to match it with a slowly varying gravitational constant while not spoiling its successes. To do so, Dirac suggests the use of two sets of units: ds_E for the Einstein field equations and ds_A for the atomic apparatus. This kind of model is still used now, under the name of bi-metrics models. All laboratory measurements of distances and times are linked to ds_A. The scales of ds_E can not be measured directly, only in equations of motion, e.g the calculation of the motion of planets involves ds_E. The link between the two metrics in the

[6]Dirac 1974.

context of orbiting planet is explained in the following box.

The two metrics can be connected, by using the Newtonian law of the circular motion of Earth around the Sun $GM = v^2 r$. In Einstein units, $G_E M_E = v_E^2 r_E$ is constant and conserved. In atomic system, $G_A M_A = v_A^2 r_A$ with $G \propto t^{-1}$, the variation of the mass M_A depends on the kind of creation process.

In the additive creation, the number of nucleons in a star is constant, so M_A. The variation of G is related to $r_A \propto t^{-1}$. The two metrics are linked $ds_A = t^{-1} ds_E$. The solar system is contracting.

For multiplicative creation, $M_A \propto t^2$ and the distance varies as $r_A \propto t$. The metrics are connected with the law $ds_A = t\, ds_E$. The solar system is expanding.

9.3.1 Additive creation

The matter creation required by the Large Numbers hypothesis can be uniform throughout space, that is the additive creation. In this configuration, the two metrics are linked by the inverse of the epoch, $ds_A = t^{-1} ds_E$. One of the first observations that could confirm this idea would be the measure of the decreasing Earth-Sun distance. Dirac references Shapiro's experiments. Those could be the measurements of echo delays of laser signals presented in Shapiro's 1976 article[7]. Dirac's model of additive creation has to consider a null cosmological constant, as explain in the next sidebar.

Assuming a not null cosmological constant λ, the quantity $\lambda^{-1/2}$ is a huge distance, of the order of magnitude of the radius of the universe.

[7] Shapiro 1976.

By dividing this quantity by the atomic unit of distance, we obtain a large number determined by the Large Numbers hypothesis.

$$\frac{\lambda^{-1/2}}{ds_E} \approx 10^{39} \propto t$$

With a constant λ, $ds_E \propto t^{-1}$, which is a property of the multiplicative creation. Seeing that, the cosmological constant must be null for the additive creation to occur (as $ds_A = t^{-1} ds_E$).

However, the creation of matter uniformly throughout space threatens the conservation of the mass. To save Einstein's equations, which require mass conservation, Dirac imagines the creation of hydrogen atoms and, also, a distribution of negative mass. This negative mass is not observable and must have no physical effects apart from curving space. The atoms of hydrogen condense into nebulae and stars, and form the observed matter while the negative mass remains uniform and unobservable.

In this theory, the total density of matter is null; except for local irregularities where the ordinary matter is condensed. This corresponds to a flat space-time, just like Minkowski's space, where the mass of nucleons is constant in Einstein's units.

9.3.2 Multiplicative creation

The matter creation required by the Large Numbers hypothesis can be proportional to the existing amount of matter, that is the multiplicative creation. In this configuration, the two metrics are linked by the epoch $ds_A = t\, ds_E$. One of the first observations that could confirm this idea would be the measurement of the increasing Sun-Earth distance. Such a model can consider a cosmological constant.

To conserve the constancy of the masses of classical bodies, this theory requires that all atomic particles masses vary like $m \propto t^{-2}$ (cf. next technical box).

In the multiplicative creation hypothesis, the dynamical time $\tau = log(t)$ the atomic time.

The ratio between the gravitational and the electric forces in a hydrogen atom is $\frac{e^2}{Gm^2} \simeq 10^{39} \propto t$. In Einstein units, G is constant and $m \propto t^{-2}$, hence $e \propto t^{-3/2}$ and $h \propto t^{-3}$.
The only static model with a positive mass that can be considered is Einstein's cylindrical model.

Furthermore, in Einstein's units, the galaxies are not receding but kept approximately at a constant distance. The observed redshift is then explained because the atomic clock is continually speeding up. The galactic light has been emitted in the past when the atomic clock was slower. Its wavelength is constant but measured at the reception with the new atomic clock, therefore the wavelength seems larger.

One of the most important problems of this theory is the crystal configuration. Dirac wonders what happens to crystal structure when matter is created where there is already some matter. The problem could be ousted by considering an extremely small rate of multiplication. However, studying structures with geological ages raises insuperable difficulties.

9.4 Microwave Radiation

Considering the radiation currently termed the Cosmic Microwave Background, Dirac's position during the 70s is unclear. In a public lecture given in 1975[8], Dirac concludes that a primitive fireball (the Big Bang) is not consistent with the Large Number hypothesis. The microwave background requires another kind of explanation, possibly an intergalactic origin. Some years later, Dirac is less unequivocal[9]. Dirac evokes the microwave radiation which appears to be a black body radiation. The following boxes present the link between temperature and epoch and, the potential contradiction between the observed CMB and the Large Numbers hypothesis.

[8] Dirac 1975.
[9] Dirac 1979.

Each spectral component[a] of the radiation is red-shifted, $\lambda \propto t^{\frac{1}{3}}$. The temperature T decreases as the frequency $T \propto \nu \propto \lambda^{-1} \propto t^{-\frac{1}{3}}$.

In addition, the rest-energy[b] of a proton of this radiation is given by kT, $\frac{kT}{m_p c^2} \simeq 10^{-13}$. So, according to the Large Numbers hypothesis, $\frac{kT}{m_p c^3} \propto t^{-\frac{1}{3}}$, thus $T \propto t^{-\frac{1}{3}}$

[a] λ is here the wavelength and not the cosmological constant.
[b] Here, k is the Boltzmann constant.

The microwave radiation thus provides confirmation of our present picture. The radiation has been cooling according to the $t^{\frac{-1}{3}}$ law since a time close to the Big Bang. According to the usual views it has been cooling according to the t^{-1} law since a certain decoupling time, when it became decoupled from matter. this decoupling time must have been around $t = 10^{26}$, when T was 10^{13} times greater than now, so that kT was approximately $m_p c^2$. The existence of such a decoupling time, playing a fundamental role in cosmology, would contradict the L.N.h.[a]

[a] Ibid., p.23.

This cosmological model is quite complete and very interesting. It combines a strong intuition, the Large Numbers hypothesis, and specific attentions to contemporary observations and experiments. Even if Dirac has never abandoned the idea of the variation of G, his cosmological model has not successfully passed to posterity.

Chapter 10

Quasi-Steady State Theory

I grew up with the erroneous notion that the scientific establishment welcomes progress, which is the opposite of what is generally true.

Home is where the Wind Blows -Fred Hoyle-

In this chapter:

- An introduction to the Quasi-Steady State Theory
- Another explanation of the microwave background
- Another explanation of the Quasi-stellar objects

As explained in chapter 7, in 1948 Fred Hoyle suggested a new model of the universe, requiring a continuous creation of matter. In chapter 8, are expounded the development of this model and its interpretations of observations such as the microwave background and Quasi-Stellar Objects. Fred Hoyle has never abandoned his idea and during the 90s publishes a new version of his model, which becomes the Quasi-Steady State Cosmology. In this chapter, evolution of the model is studied, looking at every important aspects that lead to the new cosmological model.

10.1 Creation of matter

In the previous version of Hoyle's model, matter creation could occur everywhere with a really small creation rate. In the new model[1], the creation is not

[1]Hoyle, Burbidge, and Narlikar 1993.

homogeneous in space-time, it occurs only in a strong gravitational field; but, in these conditions, the creation rate is far from small. The matter is created in the form of Planck particles, defined in modern terms in the next sidebar.

Planck particles are hypothetical subatomic particles. They are characterised by a radius equivalent to the Planck length and by a mass equal to Planck mass.
$l_{Planck} = \sqrt{\frac{G\hbar}{c^3}} \simeq 10^{-35}$ m
$m_{Planck} = \sqrt{\frac{c\hbar}{G}} \simeq 10^{-8}$ kg
Planck particles are minuscule black holes with the Compton length equal to the Schwarzschild radius.
These units are now characteristic size of string studied in the so-called theory of strings.

Studying a finite volume V of space-time, in each configuration of this volume the action $\mathcal{A}$ can be computed. When V is large, it is determined by $\delta\mathcal{A} = 0$. And the action can be linked to the mass and their world-lines. The next boxes are one excerpt describing the freedom of choice of the volume V and a technical development of the previous action $\mathcal{A}$.

It is this freedom to choose V anywhere which gives physical laws their universality. Yet it is this deep-rooted and essential requirement that is flouted in big bang cosmology, and the manner of it defies normal scientific logic, giving rise in our view to the conviction that big bang cosmology cannot possibly be correct[a].

[a]Hoyle, Burbidge, and Narlikar 1993, p.439.

$$\mathcal{A} = -\sum_a \int m_a da$$

where da is an element of proper length along the path of particle a and m_a is its mass.
Big Bang cosmology restricts this equation:

$$\mathcal{A} = -\sum_a \int_{t=0} m_a da.$$

The action can be characterised by particular choices of end-points: $\mathcal{A} = -\int_{A_0} m_a da - \int_{B_0} m_b db - ...$
The scalar-field $C(X)$ expressing the pair creation is the fundamental solution of the wave equation

$$\Box_X C(X) + \frac{1}{6} R(X) C(X) = f^{-1} \sum_{A_0} \frac{\delta_4(X - A_0)}{[-g(A_0)]}$$

where f is a positive coupling, X is an event of space-time, $R(X)$ is the scalar curvature at the point X, δ_4 is Dirac's distribution in 4 dimensions and $\Box$ denotes the d'Alembert operator.

Hoyle and his collaborators use the FLRW formalism and modify the so-called Friedmann equations, as it is showed in the next technical box. The creation field C has a role to play in the cosmic dynamics. It also influences the repartition of creation centres.

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\overline{\rho} + \frac{8\pi G}{3} f\overline{\dot{C}^2}$$

$$\frac{\dot{a}^2 + k}{a^2} = \frac{8\pi G}{3}\overline{\rho} - \frac{4\pi G}{3} f\overline{\dot{C}^2}$$

where $\overline{\rho}$ is the smoothed cosmological mass density and $\overline{\dot{C}^2}$ is the smoothed $\dot{C}^2$, C being the solution of the above-mentioned wave equation.

Some conditions have to be set to keep a a real number. Besides, it could be noticed that the matter here described is stiff matter with negative energy density ($\rho = p = -\frac{f\dot{C}^2}{2}$).

Hoyle and his collaborators studied several cosmological models according to the different properties of the creation centres. This exploration is repeated in the following box.

One can now contemplate several possibilities according to the averaged properties of the creation centers:

1) It happens that the many creation centers maintain a steady value of $\overline{\dot{C}^2}$. With the k term in [second Friedmann equation] becoming negligible with continuing expansion of the universe, there is then a steady-state solution of [Friedmann] equations,

$$S(t) = e^{Ht}, \frac{3H^2}{4\pi G} = f\overline{\dot{C}^2} = \overline{\rho}.$$

The big bang claim that $S(t) \to 0$ at some finite t, whatever the model, is disproved by this case, which served in the historic role of a counterexample. Models of chaotic inflation, also contingent on the introduction of a scalar field, have provided similar examples more recently.

> *2) The creation centers are such that $\overline{\dot{C}^2}$ varies, but not much, in the time scale for the expansion of the universe. Then there is a steady-state solution with [the previous] equation holding secularly.*
>
> *3) $\overline{\dot{C}^2}$ is dominated by large creation centers with masses $\sim 10^{16} M_{\odot}$ as obtained in the next section. The activities of the creation centers are explosive and are correlated in episodes of comparatively short duration. During such episodes $\overline{\dot{C}^2}$ increases essentially impulsively, causing a sudden increase in the expansion rate of the universe with the parameter[a] q defined by $q = -\frac{a\ddot{a}}{\dot{a}^2}$ becoming sharply negative[b].*
>
> [a]This parameter was then the deceleration parameter. A negative parameter expresses an acceleration of the expansion.
>
> [b]Hoyle, Burbidge, and Narlikar 1993, p.441.

The Quasi-Steady state model chosen by Hoyle is the third possibility of the above mentioned models. The universe is oscillating, with a general expansion. During the expansion half-cycle, the creation rate decreases, going from a maximal value to a minimal one. During the contraction half-cycle, the creation rate increases, going from a minimal value to a maximal one.

10.2 Microwave background

The explanation of the microwave background in this theory is also subject to evolution. With the COsmic Background Explorer (COBE) satellite launched in 1989, the questions raised during the sixties reappear. Three articles, ascribed to Hoyle and collaborators, are of a significant interest in our purpose. Two of them are proceedings of international conferences[2,3], while the third one is a synthesis of their intention with some notable repetition[4].

Since the 60s, as the Big Bang cosmology chronologically sets the galaxies after the emission of the Cosmic Microwave Background; steady-state models set the galaxies before the emission of the microwave background. This view requires absorbing microwave radiation and translucent to other regions of the spectrum particles. The evolution in this point of the model is the nature of

[2]Hoyle and Wickramasinghe 1989.
[3]Hoyle, Wickramasinghe, and Burbidge 1990.
[4]Arp et al. 1990.

those particles. While the interstellar grains with graphite nucleus used to seem great candidates; metallic needles, also called iron whiskers, are now preferred.

Those particles are theoretically possible as the product of the condensation of metallic vapours. This process favours the linear, and no spherical, condensation and growth of the condensate leading to highly non-isotropic needles. Iron whiskers are characterised by a length of $1mm$ for a radius of 100Å. By using Mie's absorption calculation for infinite cylinder[5], the Hoyle's team's work results in a microwave opacity and translucence for other regions of the spectrum for those iron whiskers. Those theoretical particles have been studied in laboratories and seem to be observed, notably in the Crab Nebula spectrum.

Metallic needles are subject to strong radiation pressure in their native environment. This pressure causes their expulsion into extragalactic space. Indeed, iron whiskers cannot be retained for very long inside their parent galaxies[6]. With the same procedure, presented in chapter 8 for interstellar grains, metallic needles absorb and re-emit radiation in far infra-red and microwave. The following excerpt repeats Hoyle's explanation of the phenomenon.

> [...] *metallic whiskers have a remarkable ability to absorb and re-emit radiation in the far infra-red and microwave regions of the spectrum. They act as exceedingly efficient thermalisers of such fields. Had their properties been appreciated in advance of the discovery in 1965 of the cosmic microwave background*[a] *it would have seemed natural to think that they were somehow involved with the genesis of the background*[b].
>
> [a] Penzias and Wilson 1965.
> [b] Hoyle, Wickramasinghe, and Burbidge 1990, p.61.

Hoyle and his collaborators hit on the nail: the observed microwave radiation does not have to be interpreted as a cosmological event and neither has to be called the cosmic microwave background, but is a local observation comparable with a fog, as it can be seen in the next quotation box.

[5] Hoyle, Wickramasinghe, and Burbidge 1990.
[6] Ibid.

> [...] *so far as microwaves are concerned, we are living in a fog and that the fog is relatively local. A man who falls asleep on the top of a mountain and who wakes in a fog does not think he is looking at the origin of the Universe. He thinks he is in a fog*[a].
>
> [a]Arp et al. 1990, p.810.

In the oscillating universe of the quasi-steady state model, the microwave background is not only produced by iron whiskers emissions, but is also conserved and increasing from cycle to cycle. This addition prevents his natural exponential decrease.

10.3 Quasi-Stellar Objects

The interpretation and the explanation of extragalactic objects, such as radio galaxies, quasi-stellar objects, and other active nuclei, in the context of the Quasi-Steady State Cosmology, has to be linked with Arp results[7,8], especially from his 1987 book[9].

From a commonly accepted point of view, the jets, the fluxes of relativistic particles, and other observations of high energy photons are linked to the phenomena of accretion disk falling in black holes. The QSSC model has to explain them from matter creation events, in that respect the following quote is interesting. This kind of event takes place in strong gravitational fields. The creation process, located close to an event horizon, induces an important time dilatation which influences the time measurement for a remote observer. Those events can be characterised by negative pressure and are similar to inflationary cosmology[10].

[7]Arp 1966b.
[8]Arp 1970.
[9]Arp 1987.
[10]Guth 1981.

That is to say, instead of the object expanding after the creation phase as a uniform object, it is likely to emerge in a series of blobs or jerks, every blob appearing as a distinct object in its own right[a].

[a]Hoyle, Burbidge, and Narlikar 1993, p.449.

Since the 60s, the idea of a cascade of ejections remains. Hoyle and his collaborators take as an example the particular configuration of the galaxies M87 and M84[11]. The angular position of M84 in regards to M87 perfectly corresponds to the angular position of M87's jets. This improbable observation makes the case for the ejection formation process. A blob ejected from M87 evolves and becomes M84. That precise example is used in an article in favour of the QSSC model[12], but it is only one of the many cases previously studied by Arp[13].

The specific ratio $\log N - \log S$ has been studied since the 60s and is always mentioned by Hoyle in 2000[14]. The idea is to analyse $N(S)$, that is to say the number N of sources with a flux equal or superior to S. A homogeneous distribution of sources in a Euclidean space gives $NS^{3/2}$ independent of S; while in an expanding cosmology, $NS^{3/2}$ remains constant until it decreases in link with the distance of the sources. This kind of measurement abandoned by current cosmologists has its crucial importance in the QSSC model.

10.4 From steady-state to Quasi-Steady State Cosmology

In 1948, Hoyle added to Einstein's equation a field translating matter creation. During the 60s, this field evolved to express the creation or the destruction of matter at the extremities of each particle world-lines. During the 90s, the model is improved and so the creation field is modified. The following technical box presents the evolution of the mathematical model of the Steady State Theory.

[11]M87 is also known under the name Virgo A, it is a supergiant elliptical galaxy. M84 is a lenticular galaxy in the Virgo constellation

[12]Hoyle, Burbidge, and Narlikar 1993.

[13]Arp 1987.

[14]Hoyle, Burbidge, and Narlikar 2000.

1948[a]

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + C_{\mu\nu} = -\kappa T_{\mu\nu}$$

Here, $C_{\mu\nu}$ is the covariant derivative of a vector field.

1966[b]

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G \left(T_{\mu\nu} + H_{\mu\nu} \right)$$

where $H_{\mu\nu} = -f \left(C_\mu C_\nu - \frac{1}{2} g_{\mu\nu} C_\lambda C^\lambda \right)$.
Here, C_μ is a vector field.

1993[c] The field $C(X)$ is related to the points A_0 by the wave equation

$$\Box_X C(X) + \frac{1}{6} R(X) C(X) = f^{-1} \sum_{A_0} \frac{\delta_4 (X - A_0)}{\left[-g(A_0)\right]^{1/2}}$$

The C field is the fundamental solution of this equation and is now a (non-minimally coupled) scalar field.

[a] Hoyle 1948.
[b] Hoyle and Narlikar 1966b.
[c] Hoyle, Burbidge, and Narlikar 1993.

This new version of the model is based on the idea of creation in small Big Bang events ($\sim 10^{16} M_\odot$, characteristic of a cosmic scale) homogeneously distributed through space-time while the universe itself has no beginning. Hoyle and his team justify their attempt to find an alternative to current models because they are too speculative. When some scientists try to find black holes in the center of galaxies they just want to find any evidence of the strong gravitational field produced by compact objects.

This last studied model is a beautiful sophistication of the previous Steady State Theory attempts. It corresponds to such a rich phenomenology that it would deserve to be studied for itself. It echoes in many current ideas in cosmology, such as the non-linearity of the gravitation, the investigation about the equivalence principle.

Conclusions and perspectives

A force de croire en ses rêves,
l'homme en fait une réalité.

-Hergé-

It is now the time to wrap up this thesis. Originally, its subject was the development of the Steady-State Theory during the twentieth century. However, one reading leading to another, the writer of this work found herself with more steady-state cosmologies than expected and had the urge to engage in some discussions about that. Some important personalities, representative of particular variations of the model, emerged. The difficulty in presenting them as a whole was acute. The choice was made to present them chronologically, following the order of the principal publications. Doing so, it was possible to exemplify the developments of those models and, sometimes, the interactions between them.

The first part of the present work was constituted by cosmological settings on cosmological models, from the distinction between cosmogony and cosmology to relativistic theory. The second part was dedicated to the early stages of steady-state cosmological models. It included the lately discovered Einstein's draft, Dirac's model and the subsequent debate, Jordan's cosmology, and the beginnings of the steady-state cosmology by Bondi and Gold and by Hoyle. The third and last part was devoted to the development of previously expounded models, with observations and experiments. That led to the 60s steady-state cosmology, Dirac's late model, and the Quasi-Steady State Cosmology. By doing so, this work intended to offer an overview of steady-state cosmologies and some technical developments of those disregarded models.

If the history of cosmology is often reduced to the development of the Big

Bang theory, the writer hopes that the reader is now aware of how reductive this is. The Big Bang theory has been built in contrast to its opponents, the steady-state models in particular. Looking back, this history is more understandable when it is thought of as the exploration of all conceivable models made possible by the lack of observations. The idea of a universe with a beginning in a singular state can be perceived as nasty for both epistemological and physical reasons, which explains the profusion of steady-state models. Even if modern observations and experiments have seemed to rule out this family of cosmologies, the author still hopes readers gain a little respect for these attempts and their supporters.

Einstein	1931	WHAT? Draft, cosmological constant // creation
		WHY? Simplification of the equations, aesthetics and stationarity
		ABOUT WHAT? Null density, de Sitter's cosmology
		HOW? No diffusion, unpublished draft
Dirac	1938	WHAT? Coincidences -> Large Numbers hypothesis
		WHY? Enlargement of Copernicus principle
		ABOUT WHAT? Dynamics of galaxies
		HOW? Little echo
Dirac	70s	WHAT? Large Numbers hypothesis and two metrics
		WHY? Renewed interest in cosmology
		ABOUT WHAT? Integration of the CMB
		HOW? Little known
Jordan	1939	WHAT? Dirac principle, variation of G, creation of stars
		WHY? Heuristic motivation
		ABOUT WHAT? Dynamics of galaxies, geological observations
		HOW? Unsung even if Born tried to export it
Hoyle	1948	WHAT? Steady-State Theory, conservation of the density, creation of hydrogen atoms
		WHY? Problem of the age of the universe, refusal of beginning
		ABOUT WHAT? Dynamics of galaxies
		HOW? Famous, thanks to Hoyle's celebrity
Hoyle	60s	WHAT? Evolution of the SST
		WHY? Renewed interest in cosmology
		ABOUT WHAT? CMB from interstellar media, close QSO
		HOW? Well known, thanks to Hoyle's influence
Hoyle	90s	WHAT? Quasi-Steady State Cosmology, oscillating universe
		WHY? Resistance
		ABOUT WHAT? New CMB observations
		HOW? Hoyle's running out of steam

Figure 10.1: Summary of the diverse steady-state cosmological models studied in this thesis

The main result of this research work is the revamping of forgotten steady-state models, as summarised in the table above. In 1931, Albert Einstein wrote an unknown draft in which he suggested a steady-state model of the universe. His motivations seem to be the aesthetics research of the simplification of the equations and the inner conviction that the universe must remain stationary in a way. This attempt had no repercussion since he had never be published until his rediscovery in 2014.

P.A.M. Dirac enunciated the first version of the Large Numbers hypothesis, in 1937. Following this, he suggested a steady-state cosmological model based on this principle. Dirac principle is in direct connection with Copernicus principle, there are no coincidences because humanity is not at an privileged place in space-time. This model had not a large impact on the community. Be that as it may, with the revival of cosmology during the late 60s with the observation of the CMB, Dirac came back to his model and made it evolve into a two-metrics cosmological model. In the late 30s, P. Jordan also suggested a steady-state cosmological model based upon the Dirac principle. His motivations were mainly heuristic. This model integrated the observed dynamics of galaxies and tried to account for some then misunderstood geophysical observations. This model did not broadcast in the scientific community, this could be explained by the language used in his publications (German) and his polemical political past.

The most famous steady-state cosmology is Hoyle's one, the Steady-State Theory, developed in 1948. Hoyle can be seen as Dirac's heir since the last was the advisor of the first. Hoyle worked with the motivation of the refusal of a beginning and the aim to explain the dynamics of the galaxies. Hoyle was a famous scientist and his celebrity transferred to his model, which he presented, notably, during widely broadcasted radio shows. Over time, Hoyle and his collaborators made evolve Steady-State Theory. However, Hoyle's reputation struggling, his cosmological model lost its influence and became a toy model for few initiates.

Alas, history has the sad tendency to throw the baby out with the bathwater. If steady-state cosmologies are currently put aside and despised, the inventiveness and the creativity of their ideas cannot be denied. Some concepts introduced in steady-state cosmological models are pillars of the nowadays accepted theory. The creation pockets are similar to inflationary models, the created compact objects are comparable to primordial black holes, the creation-field is analogous to the scalar field in tensor-scalar theories, etc.

Furthermore, the proponents of steady-state cosmologies are regularly victims of selective memory. Fred Hoyle is perceived as the founding father of steady-state cosmology, and his other achievements are left in oblivion. Hoyle was not the first one to dubbed the steady-state models, this honour was for H. Bondi and T. Gold. And if Hoyle supported Steady-State Theory until the end of his life, his important contribution to the famous B^2FH paper is frequently forgotten. On another note, leading figures, like Dirac or Jordan, are remembered for their contributions to quantum mechanics, without any regard to their cosmological models. One of the objectives of this thesis was to reinstate a certain authenticity on the history of steady-state cosmologies.

This text sometimes dwells at length on the epistemological aspect of the cosmological developments. The aim is to underline the profusion of ideas and their, most of the time benevolent, opposition. This a wonderful illustration of Kuhn's theory on the scientific revolution. The shift of paradigm, from Newtonian world to relativistic cosmology, is completely contained in the twentieth-century cosmology. The dialogue between ideas, the confrontations between their supporters, the resorting to experiments and observations to cut the knot are crystal clear in this polemical construction of cosmology and illustrate beautifully the parallel development of diverse models as conceived by Kuhn.

For sure, this doctoral work has raised more issues than it has solved. Some other investigations deserve to be explored in their whole thesis. A complete study of the evolution from the concept of QSO to the AGN earns a proper research. The field evolved quickly, in less than fifty years, and saw some very virulent characters in opposition. The Quasi-steady state cosmology merits also its investigation work. It could be interesting to see how it incorporated modern CMB measurements and the acceleration of the expanding dynamics of the universe. From a more sociological point of view, Hoyle's team could be put under scrutiny. The interaction with the Burbidge couple, the introduction of Narlikar and Wickramasinghe, or the link to Arp are fascinating. The author leaves these queries to future researchers and is looking forward to reading their investigations.

Part IV

Appendix

Appendix A

Translations

In this chapter, the diverse translations works from German undertaken for this research are given. A special thank should be given to D. Bertrand for his gentle and benevolent support.
In the translation, authors' conventions had been conserved, this is not the case in the corpus of this thesis.

A.1 Einstein 1931 - Zum kosmologischen Problem

To study Einstein's draft discovered and discussed by O'Raifeartaigh[1], a translation form German to French has been made.

Sur le problème cosmologique[2]

A. Einstein

La difficulté fondamentale (de principe) la plus importante qui apparaît lorsqu'on s'interroge sur la nature, est la manière dont la matière stellaire emplit l'espace en très grande dimension, comme chacun sait, dans le fait que les lois de la gravitation en général ne s'accommodent pas de l'hypothèse d'une densité de matière moyenne infinie.

[1] O'Raifeartaigh and McCann 2014.
[2] Einstein 1931a.

Déjà lorsqu'on s'accrochait à la théorie de gravitation de Newton, Seeliger avait modifié la loi de Newton en ce but par l'introduction d'une fonction d'écart, qui, pour de grandes distances, disparaît considérablement plus vite que $\frac{1}{r^2}$.

Même dans la théorie de la relativité générale cette difficulté apparaît. Mais j'ai montré par le passé que celle-ci peut être surmontée par l'introduction du terme nommé λ dans les équations du champ. Les équations du champ peuvent alors être écrites sous la forme

$$\left(R_{ik} - \frac{1}{2}g_{ik}R\right) - \lambda g_{ik} = \kappa T_{ik} \ (1)$$

$$R_{ik} = \Gamma^{\sigma}_{ik,\sigma} - \Gamma^{\sigma}_{i\sigma,k} - \Gamma^{\sigma}_{i\tau}\Gamma^{\tau}_{k\sigma} + \Gamma^{\sigma}_{ik}\Gamma^{\tau}_{\sigma\tau}$$

J'ai montré à l'époque que ces équations peuvent être résolues par un espace sphérique de rayon temporellement constant, dans lequel la matière a une densité ρ constante dans le temps et dans l'espace.

Depuis lors, il apparaît avec certitude que cette solution n'entre pas en ligne de compte pour la compréhension théorique de l'espace réel.

D'une part, il ressort des analyses de ...[3] et de Tolman basées sur les équations spatiales qu'il y a aussi des solutions sphériques avec un rayon variable temporellement P et que la solution présentée n'est pas stable relativement aux modifications temporelles de P. D'autre part, les analyses extrêmement importantes de Hubbel[4] ont montré que les nébuleuses extragalactiques présentent les deux propriétés suivantes :

1. Elles sont réparties uniformément spatialement à la limite de la précision d'observation.

2. Elles ont un effet Doppler proportionnel à leur distance.

De Sitter et Tolman ont déjà montré qu'il y a des solutions des équations (1) qui correspondent aux observations. Mais la difficulté est que la théorie conduisait constamment à un commencement temporel qui date d'environ $10^{10} \sim 10^{11}$ans, ce qui paraissait inacceptable pour différentes raisons.

Dans la suite, je veux attirer l'attention sur une solution de l'équation (1), laquelle correspondra avec les constatations de Hubbel et dans laquelle la densité est une constante temporelle. Cette solution est certes contenue dans le

[3] There is a blank in the original text.

[4] This mispelling could mean that Einstein knows Hubble's results without having read his articles.

schéma général de Tolman mais ne semble pas avoir été prise en compte jusqu'à présent. Je pose

$$ds^2 = \text{-}e^{\alpha t}\left(dx_1^2 + dx_2^2 + dx_3^2\right) + c^2dt^2(2).$$

Cette variété est spatialement euclidienne. L'écart entre deux points croît avec le facteur d'échelle avec le temps comme $e^{\frac{\alpha t}{2}}$, on confirme exactement l'effet Doppler de Hubbel, tandis qu'on donne des coordonnées constantes temporellement aux masses (distribuées uniformément, menacées). Finalement, la métrique de cette variété est constante temporellement. Car elle passe par là en utilisant la substitution $t' = t - \tau$, τ=cst, $\frac{x_1'}{x_1} = \frac{x_2'}{x_2} = \frac{x_3'}{x_3} = e^{\frac{-\alpha t}{2}}$ pour se rendre dans[5] $ds^2 = e^{\alpha t'}\left(dx_1'^2 + dx_2'^2 + dx_3'^2\right) + c^2dt'^2$. Nous négligeons les vitesses des masses relatives au système de coordonnées ainsi que l'effet gravitationnel de la pression de radiation. Le tenseur de matière est alors présenté sous la forme

$$T^{ik} = \rho u^i u^k$$

$(u^i = \frac{dx^i}{ds})$ où $T_{ik} = \rho u^\sigma u^\tau g_{\sigma i} g_{\tau k}$ (3) dans lequel $u^1 = u^2 = u^3 = 0$ et $u^4 = \frac{1}{c}$.

Les équations (1) fournissent

$$\textbf{-3}\frac{9}{4}\alpha^2 + \lambda c^2 = \text{racine carrée}$$

$$\frac{3}{4}\alpha^2 - \lambda c^2 = \kappa\rho c^2$$

ou bien $\alpha^2 = \frac{\kappa c^2}{3}\rho(4)$

La densité est donc constante et définit l'expansion jusque son signe (+/-). Si on considère un volume limité par des mesures physiques, dès lors des particules matérielles quittent constamment ce volume. Pour que la densité reste constante, de nouvelles particules de masse doivent toujours apparaître dans le volume à partir de l'espace. La loi de conservation reste maintenant par le fait que l'espace lui-même n'est pas vide d'énergie par l'accentuation du terme λ, sa validité, comme chacun sait, est garantie par les équations (1).

A.2 Jordan 1937 - Die physikalischen Weltkonstanten

For the purpose of diving into Jordan's cosmological model, a translation of his 1937 article has to be done.

[5] There, Einstein does not correct the metric.

Les constantes physiques du monde[1]

P. Jordan

Il faut être redevable aux parties essentielles développées par Eddington d'avoir mis de plus en plus clairement en lumière dans les derniers temps, le problème -ou plus encore les problèmes- des constantes naturelles physiques et astronomiques sans dimension. Par ailleurs, ceux-ci sont aujourd'hui considérés à juste titre par les physiciens comme les bases essentielles pour notre compréhension fondamentale des lois élémentaires de la physique.

Une constante sans dimension peut être construite à partir de la constante fondamentale h de la théorie quantique, de la constante e, unité de la théorie de l'électronique et à partir de la constante fondamentale c (vitesse de la lumière) de la théorie de la relativité restreinte : la célèbre constante de structure fine de Sommerfeld

$$\frac{2\pi e^2}{hc} = 0.00729. \tag{A.2.1}$$

Il est clair, dès lors, que les lois de la théorie quantique en accord avec celles de la relativité restreinte prescrivent une valeur précise de la charge électrique élémentaire e. Il doit être possible à partir d'une compréhension complète des lois quantiques et relativistes de déduire que la charge de l'électron doit avoir précisément la valeur que nous trouvons empiriquement. Ou, pour l'exprimer autrement, il doit être possible de donner une justification déductive que la constante de structure fine a précisément la valeur que nous avons définie en (A.2.1) comme une affirmation empirique.

L'unification de la théorie quantique et relativiste, donc la résolution des problèmes dans lesquels des effets aussi bien quantiques que relativistes jouent un rôle, fait toujours partie des tâches résolues de manière imparfaite.

Certes, la mécanique quantique pour des particules qui sont en mouvement lent (par rapport à la vitesse de la lumière c) est résolue et connue. Mais quand nous appliquons la mécanique aux atomes, c'est un pur hasard que la charge électrique ait précisément cette valeur, qu'elle ait empiriquement ce qui ne constituerait en aucun cas une difficulté pour l'application de la mécanique quantique. Si la charge élémentaire avait une toute autre valeur ou si différentes sortes de particules chargées existaient, dont les charges ne représenteraient pas beaucoup plus qu'une charge élémentaire. Pour la mécanique quantique (non

[1] Jordan 1937.

relativiste). Ce n'est donc pas seulement la valeur numérique mais aussi l'existence d'une charge élémentaire qui est un fait complètement indépendamment et injustifiable : il ne peut absolument pas en être autrement, parce qu'il est impossible à partir des constantes fondamentales dimensionnées qui dominent les phénomènes quantiques de définir e.

Par ailleurs, la relativité restreinte fournit un schéma général pour le traitement de phénomènes qui découlent de mouvements très rapides et ce schéma est si loin que dans son cadre l'existence et la valeur numérique empirique de la charge élémentaire apparaissent comme des faits indépendants et injustifiables. Seulement l'unification de h et de c rend possible la définition de manière dimensionnée une excellente valeur de charge et dès lors de donner au problème de la charge élémentaire une forme précise : le calcul théorique de la constante de structure fine (A.2.1) !

Mais vu que la résolution de ce problème ne peut être facile et simple, il s'en suit que la valeur numérique à appréhender est fortement différente de 1 : il est clair que seule une théorie assez compliquée pourra donner un fondement à une telle valeur numérique. Néanmoins, nous ne pouvons pas renoncer à la conviction qu'un nombre qui domine de manière si fondamentale la construction du monde physique soit défini à partir d'un contexte finalement simple. Le rapport des masses de l'électron et du proton est encore plus fortement différent de 1 ou si nous préférons le rapport inverse

$$\frac{m_p}{m} = 1,84.10^3. \tag{A.2.2}$$

.

On voudrait pour ces quatre valeurs élémentaires sans dimension exiger une explication simple. On se trouve alors face à la difficulté de concilier l'interprétation désirée avec le fait que ces deux masses soient extraordinairement différentes l'une de l'autre. On devra en tout cas, sur base du nouveau développement de la physique nucléaire, avoir tendance à considérer ce problème comme plus complexe qu'il n'apparaissait autrefois. Nous savons certes déjà qu'il existe une différence essentielle entre un électron et un proton malgré la similitude de leur charge, dans la mesure où les charges nucléaires non-électriques dont le proton est porteur n'existent pas pour l'électron (ou plutôt de manière très peu significative). La grande différence de masse est en lien avec cette diversité des champs de force d'un électron et d'un proton.

Mais nous nous heurtons à un ordre de grandeur tout à fait différent lorsque nous comparons l'effet électrique d'un électron avec son effet gravitationnel. Il existe clairement une relation constante entre l'attraction électrique et l'attraction gravitationnelle entre un électron et un proton, qui est indépendante de la distance entre les deux. Ce rapport, de nouveau un nombre sans dimension, a la valeur énorme de $2,27.10^{39}$. C'est un nombre qui sort du cadre de toute autre physique et qui a laissé apparaître la supposition qu'un lien existerait avec la constante cosmologique.

La cosmologie est cette partie de la physique (ce mot pris au sens le plus large, englobant l'astronomie) qui actuellement possède le caractère le plus spéculatif : les extrapolations les plus audacieuses portent à des conclusions qui vont loin, et une série d'analyses différentes de ces dernières années a montré à nouveau que les réflexions les plus différentes sont justifiables.

Bien sûr ces différences, dans de nombreux cas, ne signifient pas tant des divergences vraiment fondamentales que la diversité des modèles (= formes de représentation). Un exemple possible est de représenter les mêmes faits d'une part par une représentation d'un univers en expansion et d'autre part la représentation d'un changement temporel effectif des constantes de la nature.

Et, naturellement, il serait erroné de penser que deux conceptions de cet ordre doivent nécessairement se contredire. Si le cas se présente où les deux (conceptions) correspondent en ce qui concerne les conséquences à propos des faits observationnels, alors les deux conceptions sont perçues comme des descriptions équivalentes de ces mêmes faits. Il est seulement possible d'introduire des raisons de confort, de simplicité ou de clarté au profit de l'une ou de l'autre.

Par ailleurs, la situation de la cosmologie est aujourd'hui caractérisée par l'incertitude qui laisse apparaître de manière très souhaitable le fait de distinguer clairement un acte d'observation comme tel -indépendant d'une théorie - et ce qui apparaît comme le résultat d'une réflexion théorique ; nous voulons garder à l'esprit les faits d'observation et dès lors considérer ce qu'ils veulent dire.

Si on fait fi de détails plus pointus dont la signification fondamentale n'est pas encore à apprécier maintenant de manière définitive [2], dès lors il y a cinq nombres qui caractérisent le contenu de notre savoir cosmologique. À savoir, le premier et le deuxième, les constantes fondamentales c et κ de la relativité restreinte et générale ; le troisième est la densité de masse moyenne de l'univers μ ; le quatrième, la constante de Hubble α et en cinquième, l'ordre de grandeur

[2] Je voudrais également ajouter celui récemment signalé par Hubble (HUBBLE 1936a).

de l'âge du monde A. Leur valeur et leur dimension sont :

$$\begin{cases} c = 310^{10} cm/s \\ \kappa = \dfrac{8\pi f}{c^2} = 1.81.10^{-27} cm/g \\ \mu = 10^{-30} g/cm^3 \\ \alpha = 1.8.10^{-17}/s \\ A = 10^{10} ans = 3.10^{17} s \end{cases} \tag{A.2.3}$$

La constante κ est définie ci-dessus en renvoyant à la constante gravitationnelle de Newton f. Les valeurs μ et α présupposent que les définitions modernes de la distance en astronomie soient correctes. Nous voulons accepter cette hypothèse comme irréfutable. Certes, ces définitions de la distance reposent sur un système d'extrapolation en chaîne audacieux et présenté avec art ; néanmoins, il pourrait être déplacé de considérer les résultats de ces définitions comme essentiellement transformables ou incertains.

Pour la définition de μ, on doit encore approfondir la masse moyenne des nébuleuses spirales extragalactiques qui est estimée à 10^9 masses solaires ; la masse du Soleil est de $2, 10^{31} g$. Pour le reste, la définition de μ est une affaire de décompte statistique de cette nébuleuse spirale. Avec la constante de Hubble, la situation est telle que la nébuleuse spirale lointaine montre un décalage vers le rouge (*redshift*) des raies spectrales, et certes, comme l'expérience le prouve dans tout le spectre d'une seule nébuleuse spirale, la modification de fréquence $\Delta\nu$ d'une raie spectrale est proportionnelle à la fréquence ν de cette raie. De la même façon, le report-Doppler dans le spectre d'une quelconque étoile fixe, comme nous calculons l'effet Doppler pour une étoile fixe en une composante radiale de la vitesse

$$v = \frac{\Delta\nu}{\nu c}. \tag{A.2.4}$$

De même nous pouvons exprimer le redshift établi pour une nébuleuse spirale au moyen de la valeur de la vitesse établie selon (A.2.4).

Nous voulons soutenir fermement que, sur ce point, aucune hypothèse ne se bloque, cela peut nous être par ailleurs totalement égal. Soit, nous expliquons ce redshift des nébuleuses spirales comme un effet Doppler ; soit, nous nous réservons d'autres interprétations possibles : la vitesse de fuite de la nébuleuse calculée selon (A.2.4) doit être pour nous seulement une mesure pour le redshift observé -conformément à notre intention de récolter nous-mêmes des faits observables.

L'expérience prouve par ailleurs qu'il existe une proportionnalité des vitesses de fuite avec les distances des nébuleuses distinctes. Divisons donc la vitesse de fuite d'une nébuleuse par sa distance, nous obtenons (de manière proche) toujours le même nombre, dont la dimension est l'inverse du temps, qui est la constante de Hubble α.

L'âge du monde A n'est définissable que selon l'ordre de grandeur mais il a par contre l'avantage d'être indépendant des définitions de distance en astronomie. À partir de la définition de l'âge de roches radioactives, il est connu que l'on peut définir l'âge de la Terre de manière fiable et, de manière surprenante, il est apparu que celui des météorites – également celles qui sans aucun doute ne proviennent pas du système solaire - ne vont pas jusqu'à celui de la Terre. La représentation, dont on s'est rapproché par cela, selon laquelle tout notre univers n'est pas en ordre de grandeur plus vieux que la Terre mais trouve un support dans plusieurs autres faits astronomiques et n'est en contradiction avec aucun fait connu. Par ailleurs, on a le modèle précédent selon lequel les différents types d'étoiles sont des états de développement d'un seul développement stellaire, qui a dû être abandonné, vu qu'il menait à des calculs de l'âge de l'univers d'au moins 10^{13} ans.

Nous pouvons maintenant construire, à partir de ces cinq valeurs numériques, deux constantes sans dimension c'est-à-dire

$$\begin{cases} \alpha A = 5,4 \\ \dfrac{\alpha}{c\sqrt{\kappa\mu}} = 15 \end{cases} \tag{A.2.5}$$

Ce résultat est très remarquable : les constantes sans dimension sont de l'ordre de 1 ! Il existe donc des rapports très simples entre elles, l'explication théorique de nos données expérimentales cosmologiques calculées sera plus simple comme le cas de la constante de structure fine et le rapport entre les masses de l'électron et du proton. Naturellement, il ne faut pas accorder trop de poids aux valeurs numériques dans (A.2.5), et nous voulons poser, de manière généreuse, les deux valeurs numériques égales à 1 pour la suite du débat. À côté des constantes sans dimension de (A.2.5), nous pouvons calculer à partir de nos cinq nombres, respectivement une constante naturelle cosmologique de dimension de masse, de dimension de longueur et de dimension de temps. Après que les constantes sans dimension aient été mises à 1, ces valeurs à calculer maintenant sont clairement définies comme suit

$$\begin{cases} M = \dfrac{1}{\sqrt{\kappa^3 \mu}} = 1.3.10^{55} g \\ R = \dfrac{1}{\sqrt{\kappa\mu}} = 2.5.10^{28} cm \\ A = A \end{cases} \tag{A.2.6}$$

Notons dès lors, par ailleurs, quelques rapports dont la validité est une conséquence du fait que nos deux nombres sans dimension sont pratiquement égaux à 1.

$$\begin{cases} R = \kappa M \\ \mu R^3 = M \\ R = cA \\ \alpha R = c \end{cases} \tag{A.2.7}$$

Tout ceci constitue, en insistant à nouveau, une conversion de faits expérimentaux complètement sans hypothèse. Si nous nous permettons maintenant de réfléchir dans ces contextes empiriques, alors il peut être difficile de donner une explication plus simple et plus claire que celle développée par Lemaître qui apparaît environ comme suit. Le monde est apparu il y a 10^{10} ans d'une explosion primitive. L'espace est de taille infinie, son rayon est d'ordre de grandeur R et son volume est donc d'ordre de grandeur R^3. Nous constatons à partir de (A.2.7b) que M est l'ordre de grandeur pour la masse globale de l'univers, appelé (A.2.7d) ; que les nébuleuses les plus éloignées de nous (de distance R) s'éloignent de nous précisément à la vitesse de la lumière, appelée (A.2.7c) ; que, dans le cadre de la constante temporelle α, l'âge du monde A suffit précisément à laisser croître le rayon du monde à partir d'une valeur originelle qui pourrait être presque nulle jusqu'à sa valeur actuelle. Finalement, (A.2.7a) dit que le rayon du monde R correspond à l'ainsi nommé rayon gravitationnel de l'univers (d'ordre de grandeur κM). On observe mieux le sens physique propre de cette correspondance (d'après la remarque de Haas) lorsqu'on transforme (A.2.7a) en

$$\kappa \frac{M^2}{R} = M. \tag{A.2.8}$$

Cela signifie notamment que (en faisant abstraction ici du facteur numérique d'ordre 1) l'énergie au repos Mc^2 provenant de la masse globale M (définie par addition de différentes masses de toutes les nébuleuses spirales) est égale à l'ensemble de l'énergie gravitationnelle potentielle (négative) de l'univers. La masse propre de l'univers, notamment celle dans laquelle la partie d'énergie gravitationnelle négative est comprise, est nulle.

Les recherches de Georges Lemaître ont montré que l'explication des relations (A.2.5),(A.2.6),(A.2.7) ici esquissée est applicable en effet d'une manière mathématiquement entièrement incontestable sur base de la géométrie de Riemann et de la relativité générale ; en outre, il s'impose naturellement des relations exactes à la place de celles d'ordre de grandeur de masse. Relations que nous avons envisagées plus haut. Mais, on devra admettre que cette explication est si simple et si évidente qu'on ne peut le souhaiter. C'est pourquoi je voudrais croire que les nouveaux, et importants, résultats observables que Hubble a exposé récemment, se laissent finalement au cadre de cette image, bien que Hubble lui-même en a tiré la conclusion sensationnelle que l'explication du redshift au sens de Lemaître serait impossible [3].

Les éléments de mesure cosmologiques M, R, A, n'obtiennent leur propre contenu physique qu'au travers de la prise en compte des éléments de mesure de la physique atomique correspondants. Comme telle, nous choisissons la façon la plus efficace

$$\begin{cases} m_p = 1,65.10^{24} g, \\ \Lambda = \dfrac{e^2}{mc^2} = 3.10^{-13} cm, \\ \tau = \dfrac{\Lambda}{c}. \end{cases} \tag{A.2.9}$$

Naturellement, le fait que les constantes sans dimension (A.2.1) et (A.2.2) de la physique atomique ne sont pas d'ordre 1, conditionne un certain arbitraire dans le choix de ces éléments de mesure de la physique atomique. Nous aurions pu choisir au lieu de la masse du proton, la masse de l'électron et à la place de l'élément de longueur Λ, qui correspond au rayon de l'électron de même ordre de grandeur que le rayon des noyaux atomiques ; nous aurions pu utiliser la longueur de Compton-Wellen ou aussi l'ordre de grandeur $\dfrac{h^2}{4\pi^2 me^2}$ du rayon atomique :

$$\begin{cases} \dfrac{h}{mc} = 2,41.10^{-10} cm \\ \dfrac{h^2}{4\pi^2 me^2} = 0,532.10^{-8} cm. \end{cases} \tag{A.2.10}$$

Mais le choix posé est plus approprié pour la suite. En comparant les éléments de mesure (A.2.6) avec (A.2.9), nous obtenons deux nouveaux nombres

[3]Voir la note de bas de page S.514

sans dimension ; nous notons en même temps leur quotient

$$\begin{cases} \frac{M}{m_p} = 10^{79} \\ \frac{R}{\Lambda} = \frac{A}{\tau} = 10^{41} \\ \frac{\frac{M}{m_p}}{\frac{R}{\Lambda}} = \frac{1}{8\pi}.2,27.10^{39} \end{cases} \tag{A.2.11}$$

De ces trois nombres, le premier est visiblement à considérer comme le nombre de protons et de neutrons dans l'univers. Le troisième a la remarquable propriété d'être indépendant de la densité de masse moyenne μ ; il veut visiblement signifier le rapport entre l'attraction de Coulomb entre un proton et un électron et leur attraction Newtonienne divisée par 8π.

Le deuxième de ces nombres (A.2.11) pourrait aussi être exprimé comme le quotient du premier et du troisième et vu qu'on a habituellement préféré cette façon de l'exprimer ; ainsi, on n'a pas suffisamment accordé d'attention à ce que Dirac a développé[4] et à ce que nous avons fait connaître en (A.2.11) : ce nombre sans dimension ne signifie rien d'autre que l'âge du monde mesuré dans l'élément de temps $\tau = \dfrac{\Lambda}{c}$ comme unité. Ce nombre sans dimension n'est en aucun cas une constante- il évolue linéairement avec le temps, encore qu'avec une croissance si petite qu'elle doit être envisagée à l'intérieur de l'histoire humaine passée et future comme invariante en pratique. Mais, comme Dirac en avait parlé, ceci est avant tout simplifiant et rassurant : nous n'avons pas besoin dès lors d'essayer de trouver un fondement théorique pour cette apparition d'une constante naturelle sans dimension de l'ordre de grande colossal de 10^{41} ! Car la valeur actuelle de ce nombre est purement accidentelle : après 24h, elle grandit de 3.10^{28}. On peut peut-être espérer que le nombre encore plus grand $\dfrac{m}{m_p}$ est à concevoir de manière correspondante. Il existe visiblement jusqu'à un facteur relativement petit la relation :

$$\frac{M}{m_p} = \left(\frac{R}{\Lambda}\right)^2 . \tag{A.2.12}$$

Et si ceci n'est pas purement un hasard mais un lieu nécessaire selon la loi de la nature, il s'ensuit dès lors, comme Dirac le prétend, à partir de la croissance temporelle de $\frac{R}{\Lambda}$ une croissance correspondante de $\frac{m}{m_p}$.

Nous avons ici établi que la masse globale qui vient de la somme de la masse au repos de toutes les particules de matière de l'univers est globalement

[4] Dirac 1937b.

compensée par l'énergie gravitationnelle négative ; c'est pourquoi il n'existe en aucun cas une difficulté de la part de la conservation de l'énergie de se représenter que l'expansion spatiale de l'univers soit accompagnée d'une production continue de matière. Ce serait alors la mission d'une théorie de cette création[5] de matière astrophysique largement développée (complète) d'expliquer le fondement de pourquoi le relation (A.2.12) entre l'expansion et la production de matière doit exister. Si cette représentation de Dirac est exacte, la constante gravitationnelle κ doit visiblement décroître continuellement, inversement proportionnelle au temps passé depuis le début du monde, de sorte que cette constante gravitationnelle ne mérite pas le nom de constante.

Si on essaie par contre de considérer (A.2.12) comme dû au hasard, c'est-à-dire comme valable seulement aujourd'hui, alors on envisage encore d'autres possibilités, mais la tâche reste en tout cas de trouver une interprétation pour une grandeur cosmologique colossale. Des possibilités évidentes seraient de considérer soit $\frac{M}{m_p}$ soit κ comme des constantes, nous laisserons cela à des recherches futures. La parution d'un nouveau livre d'Eddington a fourni l'occasion à l'auteur d'étudier ces questions et de rédiger cet essai. Depuis un certains nombre d'années, Eddington a traité dans plusieurs recherches le problème des constantes sans dimension de la nature.

Les efforts expérimentaux en vue d'une évaluation la plus précise possible de la constante de structure fine par la combinaison de mesures de précision de la physique atomique ont donné une impulsion fondamentale au travers des réflexions sensationnelles d'Eddington sur ces questions.

La parution d'un livre, dans lequel Eddington ne donne pas seulement le résumé systématique de ses recherches faites précédemment mais aussi, en même temps, des compléments essentiels et des perspectives, serait dès lors considérée par les physiciens comme un événement si cet auteur n'était pas connu de manière universelle comme l'un des plus brillants orfèvres scientifiques de notre époque et comme l'un des représentants les plus marquants des hautes traditions britanniques.

Comme continuité et complément de son œuvre la plus connue « *Relativity*

[5] L'auteur de la présente traduction a décidé d'utiliser le terme *création* de façon à pouvoir le mettre résonance avec les modèles postérieurs de Bondi et Gold et celui de Hoyle. Il est à noter que le terme originel en allemand n'est ni *Schöpfung*, ni *Erstellung*, ni même *Kreation*. Jordan a utilisé le mot *Entstehung* qui est plus proche de la notion d'*émergence*. Ceci n'a dès lors aucun lien avec la creéation *ex nihilo* au sens théologique ou métaphysique, mais concerne plutôt un procédé de fabrication à partir d'un substrat.

Theory of Protons and Electrons[6] » , le nouveau livre vise une unification des théorie quantique et atomique au sein de la théorie de la relativité : « *J'avais pensé à une harmonisation plutôt qu'à une unification de la théorique quantique et de la relativité.* »

La théorie relativiste du spin électronique de Dirac construit un pont vers ce nouveau domaine ; pont qui, par la découverte des spins indépendamment de toute théorie quantique ou de l'électron, a apporté un enrichissement tellement attendu et formidable à la relativité précédemment limitée aux tenseurs.

Partant de l'étude de ces spins et des célèbres matrices de Dirac, Eddington développe ses propres lignes de pensées, lesquelles conduisent à la définition théorique des constantes de structure fine et du rapport des masse du proton et de l'électron. On ne peut pas prétendre que le chemin dans cette direction soit simplement une déduction des lois de la théorie quantique et relativiste déjà connues et assurées par l'expérimentation ; et, dès lors, on ne peut pas prétendre que les valeurs découvertes avec des raisonnement incontournables logico-mathématiques soient les bonnes.

Il s'agit bien plus pour Eddington de lire, en considérant ce que nous savons déjà, la possibilité d'un approfondissement de notre compréhension des lois élémentaires de la physique ; au-delà de cet approfondissement - dont l'exactitude reste définitivement à trancher, en étant sujet d'expérimentation - il est possible de définir les constantes en question. Les résultats d'Eddington sont

$$\frac{hc}{2\pi e^2} = 137; \frac{(m_p + m)^2}{m_p m} = \frac{(136)^3}{10.137} \tag{A.2.13}$$

Les recherches suivantes d'Eddington concernent aussi dès lors les nombres cosmologiques sans dimension. Indépendamment (en s'écartant) de la réflexion de Dirac - qui a été premièrement stimulée par le livre d'Eddington - il conçoit aussi ces deux nombres sans dimension comme constants. Ses réflexions le conduisent d'une part à une analyse et une justification de la mystérieuse relation (A.2.12) et d'autre pas à l'établissement théorique que

$$\frac{M}{m_p} = 136.2^{256} \tag{A.2.14}$$

Il faut laisser à l'avenir de décider si ces considérations audacieuses - là aussi , où selon la remarque de Dirac elles correspondent à une des différentes

[6] Eddington 1936.

représentation de la théorie de Lemaître - doivent être gardées telles qu'elles en tous points.

Il est, par contre, certain que le nouveau livre d'Eddington deviendra source de stimulation importante et féconde pour la recherche physique. Quelques pensées philosophique qu'Eddington laisse apparaître dans son livre semblent (apparaissent) attirantes et profondes comme toujours chez Eddington.

A.3 Jordan 1938 - Zur empirischen Kosmologie

Jordan develops his study of dimensionless numbers in a cosmological model there it is its translation.

De la cosmologie empirique [1]

P. Jordan

§1. En résumé, j'ai montré dans cette revue [2] que les questions cosmologiques dans leurs grandes lignes peuvent être estimées complètement indépendantes des théories compliquées et à certains égards incertaines sur lesquelles est fondée la grande partie des constructions de modèles cosmologiques. Si on n'exige pas tout de suite une relation numérique précise entre les constantes caractéristiques des modèles cosmologiques, mais qu'on aspire seulement à une orientation en ce qui concerne les ordres de grandeur, alors on peut, par de pures réflexions dimensionnées, déduire ce que l'on souhaite des données empiriques. Cette procédure devrait être préférée pour les développements futurs de la cosmologie par rapport à des tentatives de déductions théoriques après que les bases empiriques pour l'appréciation des questions cosmologiques se soient nettement répandues et se répandent encore ; une façon de voir les choses, qui se lie aussi étroitement que possible aux faits empiriques et qui renonce aux théories trop spécialisées, sera la plus appropriée[3]. Dans ce sens, mes réflexions précédentes doivent être complétées par la prise en compte de matériaux et des points de vue ultérieurs.

[1] Jordan38

[2] La connaissance de cet article précédent JORDAN 1937 ne sera pas nécessaire, mais utile, pour comprendre celui-ci.

[3] Cependant, toute détermination factuelle qui va au-delà de l'enregistrement des résultats d'un instrument de mesure individuel est un produit de consolidation de travaux expérimentaux et théoriques. Bien entendu, les remarques ci-dessus n'entendent pas être en accord avec les tentatives de construire artificiellement une opposition entre travail expérimental et théorique.

§2. Si nous exprimons qu'une longueur définie astronomiquement, environ le rayon du monde R, défini comme $R \cong \frac{1}{\sqrt{\kappa\mu}}$ (dans lequel comme autrefois $\kappa = \frac{8\phi f}{c^2}$ la constante de gravitation relativiste à déduire de la constante de gravitation newtonienne f, et dans lequel μ est la densité de masse moyenne de l'univers), dès lors cette affirmation ne mérite naturellement alors un véritable contenu que lorsque nous considérons comme constante une mesure de longueur d'après la définition. Une telle mesure de longueur nous est fournie par la physique atomique sous la forme de Compton-Wellen $\frac{h}{mc}$ ou du rayon de l'électron $\frac{e^2}{mc^2} \approx 10^{-13} cm$. Vu que la constante de structure fine $\frac{2\pi e^2}{hc}$ doit probablement être considérée comme une constante absolue, bien que selon l'analyse théorique elle est encore non comprise, alors l'établissement de la constante par définitions de l'un ou l'autre de ces valeurs de longueur est équivalente.

Lorsque nous définissons en pratique cette unité de longueur par une tige de platine ou par la longueur d'onde d'une certaine raie spectrale du cadmium, alors, visiblement, en principe, cela est la même chose que le retour à la mesure de longueur de la physique atomique. Car ces mesures de longueur pratiques sont en relation constante et immuable avec l'unité de longueur définie par la physique atomique. La théorie du spectre de l'atome de cadmium et la théorie de la mécanique ondulatoire du métal platine établissent le lien sans que d'autres constantes de la nature indépendantes ne rentrent en jeu [4].

Il n'en va pas de même avec les mesures du temps. Pour celles-ci une unité est conservée pour autant qu'on divise l'unité de longueur par c. Les horloges physiques les plus précises, à savoir celles qui fonctionnent sur base de la pulsation piezo-électrique, ne fournissent alors qu'une mesure du temps établie en relation stable avec l'élément de temps lorsqu'il est certain qu'on peut accepter les masses des noyaux atomiques présents dans les cristaux en question comme dans une relation invariante avec la masse de l'électron. Une hypothèse qui va encore plus loin est nécessaire lorsqu'on veut considérer les mesures géologiques du temps qui suivent les recherches sur la radio-activité comme en relation invariante avec l'élément de temps $\frac{e^2}{mc^3}$: il faut dès lors également accepter une invariabilité des forces nucléaires. Nous voulons provisoirement supposer que ces hypothèses puissent être confirmées – bien que vu la connaissance fragmentaire actuelle des relations éventuelles entre les forces de liaisons atomiques et les autres forces (gravitation) ne paraissent absolument pas certaines. Nous y reviendrons plus tard.

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[4] Au moins dans l'approximation dans laquelle on peut considérer ici les masses nucléaires de Cd et Pt comme infinies

Weyl a, comme chacun sait, fait remarquer à l'époque que, contenue dans la géométrie riemannienne, l'hypothèse géométrique d'un report d'échelle intégrable représente aussi peu une nécessité logique que l'hypothèse géométrique - prise en compte dans la géométrie d'Euclide mais abandonnée dans celle de Riemann. Si je pose deux baguettes parallèles côte à côte et ensuite je les déplace de telle manière que chacune est dans la position reportée infinitésimalement encore parallèle à la position précédente, dès lors, les deux baguettes resteront parallèles si après avoir parcouru deux chemins différents elles reviennent au même point dans le cas d'un espace euclidien plat, ce n'est pas dans le cas d'un espace de Riemann courbé en général (comme on peut facilement se le représenter par le double transport parallèle de deux baguettes tangentes à la surface terrestre courbe). Comme chacun sait, la théorie de la gravitation fournit des raisons de considérer la géométrie Riemannienne et non celle d'Euclide comme donnant la norme pour l'évolution physico-géométrique des mesures authentiques (par exemple produites à partir du platine).

La géométrie explorée par Weyl, qui va au-delà de celle de Riemann en tant que généralisation, conduit à ce que, en s'écartant de la géométrie d'Euclide et de Riemann, deux mesures considérées de même longueur ont pu avoir des longueurs différentes après un transport par des chemins différents. Mais on peut mentionner des raisons empiriques astrophysiques pour le fait que ce genre de choses ne se produit pas avec de véritables mesures (donc pour la longueur $\frac{e^2}{mc^2}$). Car toutes nos expériences spectroscopiques mènent à ce que le principe général suivant soit correct :
Un atome - disons environ un atome de Na - qui peut se trouver quelque part dans l'espace et qui peut réaliser une petite émission de lumière perceptible par nous, montre un spectre dont les fréquences ν^* sont conformes, jusqu'à un facteur égal pour toutes les fréquences, aux fréquences spectrales ν correspondantes d'un atome Na terrestre :

$$\nu^* = const.\nu. \tag{A.3.1}$$

Le facteur, quant à lui, ne dépend plus que de l'état de mouvement de l'atome en question et du potentiel gravitationnel de là où il est ; en conséquence il est le même facteur par exemple pour toutes les raies spectrales de l'étoile.

Cette loi générale, d'après notre expérience, remplit, montre et fournit en fait la base propre pour l'introduction de l'unité de longueur de la physique atomique (ou du centimètre se trouvant en relation stable d'après ce qui est exprimé ci-dessus) comme celle d'une unité de longueur d'une mesure en relation avec laquelle des changements de longueurs cosmologiques peuvent-être mesurés.

§3. Néanmoins, on ne peut pas dire que cette façon d'établir les longueurs soit la seule possible ni qu'une autre façon de faire puisse conduire à une théorie de contenu physiquement différent. Une autre façon tout aussi possible de formuler les longueurs correspondrait à poser le rayon R comme une constante. Le fait que le rapport $R = \frac{e^2}{mc^2}$, après manifestation de l'effet d'Hubble, croît avec le temps peut donc être exprimé de sorte que R croît pendant que $\frac{e^2}{mc^2}$ reste constant ou aussi de sorte que $\frac{e^2}{mc^2}$ décroît pendant que R reste constant. C'est purement une différence de façon de s'exprimer sans que quoi que ce soit de différent ne soit dit.

Cette conception que R puisse être constant mais $\frac{e^2}{mc^2}$ puisse décroître – ce qu'on peut préciser si on fixe m constant et que e et donc h aussi diminuent- a été récemment énoncée par Sambursky[5]. C'est, d'après ses dires, insensé de se demander si cette conception peut être correcte ; on peut quant même demander si elle est appropriée – car dans le cheminement le plus logique elle ne peut en aucun point fournir une solution démontrable, qui ne serait pas non plus à exprimer par une autre explication (avec $\frac{e^2}{mc^2}$ constant et R qui croît).

Elle est donc appropriée mais pas complètement certaine ; car elle abandonne d'emblée le lien clair entre la longueur géométrique et la longueur d'un bâton réel (de platine) et elle rendrait nécessaire une conversion de l'époque géologique déduite à partir des mesures radioactives. Sambursky admet toutefois qu'une différence, concernant les faits observables, résulte des deux conceptions ; si on définit R comme constant, il croit pouvoir exposer les nouveaux résultats d'Hubble, lesquels après examen du dernier auteur construisent une preuve pour un univers statique. Mais en vérité, aucune différence de résultat physique ne peut être attendue sur base d'un choix différent d'une définition, en soi arbitraire (bien que qualifiable au travers de raisons appropriées) ; par un raisonnement logique, la théorie de Sambursky doit être aussi bien compatible que incompatible avec les nouveaux résultats de Hubble, comme l'est la théorie d'un univers en expansion.

§4. Sur base des nouveaux résultats d'Hubble[6], il s'agit de ceci : c'est un mérite d'Hubble et de Tolman[7] d'avoir énoncé que l'expansion de l'univers doit produire un effet observable autre que l'effet d'Hubble [8]. La représentation d'un monde statique, sans effet Hubble, avec un espace Euclidien plat et avec une fréquence moyenne des galaxies spirales constante spatialement, rend possible

[5] Sambursky 1937.
[6] Hubble 1936b.
[7] Hubble et Tolman 1935.
[8] Comparez à cela (Bruggencate 1936).

une distribution statistique, précise et facilement accessible, des galaxies spirales plus claires et plus foncées de la voûte céleste. Une courbure de l'espace change cette statistique d'un certaine façon ; un changement plus large se produit à partir du redshift d'Hubble. Si chaque $h.\nu$ simple, auquel on aurait pu s'attendre en l'absence d'effet Hubble, est compensé par

$$\nu^* = \frac{\nu}{\left(1 + \frac{d\nu}{\nu}\right)},$$

avec $\frac{d\nu}{\nu} = \frac{v}{c}$, où v est la vitesse de fuite de la galaxie concernée, alors la luminosité H_0, à laquelle on pouvait s'attendre lors du redshift manquant doit diminuer au moins jusque

$$H = \frac{H_0}{1 + \frac{v}{c}}. \tag{A.3.2}$$

Mais si nous pouvions appliquer ces formules, que nous aurions appliquées pour une source de lumière ordinaire qui s'éloigne de nous avec une vitesse radiale v, à la galaxie spirale qui fuit à la vitesse v, alors on obtiendrait un affaiblissement encore plus fort de la luminosité, nommément [9]

$$H = \frac{H_0}{\left(1 + \frac{v}{c}\right)^4}. \tag{A.3.3}$$

Le fait qu'il ne s'agit pas dans notre galaxie d'un mouvement individuel mais d'une partie pure à l'expansion de l'espace, fournit à la place de (A.3.3), un effet diminué

$$H = \frac{H_0}{\left(1 + \frac{v}{c}\right)^2}. \tag{A.3.4}$$

Le décompte statistique des nébuleuses, d'après Hubble, soutient (A.3.2) au lieu de (A.3.4), contre la prédiction théorique[10].

Nous avons déjà souligné le fait que l'issue tentée par Sambursky ne nous paraît pas appropriée pour résoudre la difficulté apparue. Un univers statique tel que nécessaire dans la vision actuelle de Hubble ne signifie pas la constance de R – accepter celle-ci est purement affaire de définition - mais la constance du quotient $R = \frac{e^2}{mc^2}$; du point de vue de Sambursky, on ne peut pas s'attendre à comprendre les nouveaux résultats d'Hubble.

[9]En raison de l'invariance relativiste de ρ_v/v^3

[10]Dans la formule théorique (A.3.4), il n'a pas encore été tenu en compte le fait, peut-être non-essentiel, que nous voyons les galaxies en moyenne dans un stade plus ancien en raison du chemin lumineux plus grand.

Il est d'autant plus important que Ten Bruggencate parvienne, dans une critique soigneuse des recherches d'Hubble[11], aux résultats que la précision des statistiques empiriques ne parviennent pas encore à trancher définitivement entre (A.3.2) et (A.3.4).

Nous croyons donc que le modèle esquissé dans notre essai précédent, dans lequel nous cherchions à résumer la situation actuelle de notre compréhension dans le problème cosmologique, est à considérer essentiellement comme digne de confiance et clairement imposé par les faits ; on peut le changer, d'après les définitions et la façon de le présenter mais pas dans son contenu en faits observables.

§5. La relation

$$\frac{M}{m_P} \approx \left(\frac{R}{\Lambda}\right)^2, \tag{A.3.5}$$

dans laquelle $M \approx 10^{55} g$ représente la masse de l'univers (on veut dire la somme des masses de ses particules élémentaires sans soustraction de l'énergie gravitationnelle), m_P la masse du proton et Λ l'élément de longueur. La motivation pour l'acceptation hypothétique de la relation (A.3.5) provient de ce que la valeur énorme et sans dimension $\frac{M}{m_P}$ doit être apportée, en quelque sorte, en lien simple avec $\frac{R}{\Lambda}$. Les tentatives pour construire une constante sans dimension d'une telle ampleur sur base d'une théorie physique paraissent trop peu riches en perspectives malgré la géniale sagacité (le génie) appliquée à cette mission. Par chance, $\frac{R}{\Lambda}$ n'est pas un constante, cela ne nous cause, en ce sens, aucun souci ; $\frac{R}{\Lambda}$ est égal à l'âge actuel du monde exprimé en un nombre énorme d'unité de temps $\frac{e^2}{mc^3}$. Si $\frac{M}{m_P}$ était une fonction simple de $\frac{R}{\Lambda}$, alors nous serions débarrassés aussi du même souci concernant ce nombre encore plus grand ; et après ces valeurs, la relation (A.3.5) arrive seulement sur la table. Une reformulation très remarquable de (A.3.5) a été énoncée récemment par Haas[12]. Haas fait ensuite usage du fait que, selon l'ordre de grandeur $\frac{h}{m_P c} \approx \Lambda$ est, de sorte que nous pouvons formuler aussi (A.3.5) dans la formule sûrement plus appropriée

$$Mc = h\frac{R^2}{\Lambda^3}. \tag{A.3.6}$$

Ceci invite à la lecture suivante : McR est (parce que $\frac{R}{c}$ fournit l'âge de l'univers) l'ordre de grandeur pour *l'action totale du monde* et celui-ci est, d'après (A.3.6), égal au quanta d'action de Planck h multipliée par le volume de l'univers R^3 que l'on a exprimé en beaucoup d'unités de volume élémentaire

[11] Bruggencate 1937.
[12] Haas 1937.

Λ^3. De sorte que, en moyenne, l'action h est disponible par volume élémentaire Λ^3.

§6. Si nous voyons (A.3.5), respectivement (A.3.6), comme correcte alors une création continue de matière doit prendre place dans l'univers. La conservation d'énergie est attendue comme cela a été montré dans de précédents travaux, mais nos connaissances actuelles ne nous laissent comprendre en aucune manière comment cette production de matière pourrait émerger d'elle-même. Ceci paraît d'autant plus important que certains signes empiriques plaident pour l'existence réelle d'une production de matière de grande ampleur : il existe notamment des galaxies dont l'aspect les fait paraître de manière indéniable comme bien plus jeune par rapport à d'autres. Les deux illustrations, reproduites ici en plus petites d'après Tolman[13], d'une jeune et d'une vieille galaxie spirale nous paraissent dans ce sens particulièrement impressionnant. En fait, la matière de la jeune nébuleuse est apparue plus tard que celle de l'ancienne, ceci n'est peut-être pas le seul signe possible de cette formidable apparition, mais selon nous le plus naturel [14].

Il est facile de penser, dans ce contexte, que l'origine des hauts rayonnements nous est actuellement complètement incompréhensible. L'apparition discontinue de particules avec une énergie de $10^{12}eV$ rend certes, sur bases de processus compréhensibles de nous, toute interprétation impossible, comme cela a été justement souligné[15]. L'hypothèse de Georges Lemaître qui se détourne d'une nouvelle production renouvelée de hauts rayonnements, perd en crédibilité, tandis que, par ailleurs, une création de matière constante doit être acceptée. On pourra peut-être penser d'avantage à concevoir la production de haut rayonnements comme un effet secondaire de la production de matière.

§7. Une autre conséquence importante des relations (A.3.5) et (A.3.6) est que la constante de gravitation doit décroître de manière inversement proportionnelle à l'âge du monde.

Lorsqu'on accepte ceci, on peut difficilement s'empêcher de considérer la constante gravitationnelle comme un champ scalaire qui n'est en aucun cas constant spatialement. Ce qui décroît en fait de manière inversement proportionnelle à l'âge du monde (donc également inversement proportionnelle au rayon R) ne peut être que la valeur moyenne spatiale $\bar{\kappa}$ de κ valable pour la

[13] Cet article de Tolman contient d'autres illustrations merveilleuses TOLMAN 1937.
[14] Hormis la différence des chemins lumineux associés.
[15] COMPTON et CHOU 1937.

question de l'âge du monde sur tout l'espace.

Ceci a conduit au fait que la théorie de la gravitation acceptée jusqu'ici doit être révisée et également, s'il était possible, de maintenir les équations du champ de la gravitation sous la forme connue

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \kappa T_{\mu\nu} = 0 \tag{A.3.7}$$

(dans laquelle nous avons omis le terme dit cosmologique, le R apparaissant ici n'est naturellement pas le rayon du monde R). Il serait de toutes façons nécessaire d'ajouter une équation correspondant à la nouvelle production du champ scalaire κ. Peut-être d'autres possibilités encore plus compliquées seraient à envisager. Ces questions nous placent face à de nouvelles tâches variées.

Ainsi apparaît la question urgente de savoir avec quelle précision il est permis d'égaler la valeur κ présente dans notre système solaire avec la valeur moyenne de κ nécessaire pour les calculs cosmologiques, la justesse de nos valeurs R et M en dépend de manière décisive.

§8. La représentation selon laquelle κ varierait aussi spatialement rend possible un jugement absolument inédit d'un problème fondamental de la cosmologie. Ceci a été montré par Sambursky dans le cadre de ses recherches déjà citées, l'équivalence, expliquée plus haut, de la théorie définissant R comme constant avec celle présentée ci-dessous, laquelle pose R comme croissant, rend possible la transposition de l'idée exposée par Sambursky dans le cadre dans sa formulation sans aucun problème dans notre formulation.

L'hypothèse bien fondée selon laquelle l'âge du monde n'est peut-être pas fondamentalement plus grand que 10^{10}ans - pour laquelle un nouvel argument est apparu entre temps au travers de nouvelles estimations de l'âge du Soleil [16] - semblait jusque là rendre nécessaire de renoncer à l'interprétation des différentes sortes d'étoiles fixes comme différents stades d'une évolution homogène et liée. Car les étoiles, qui seraient à considérer comme les plus jeunes dans le cadre d'une telle définition, présentent par rapport aux plus anciennes une masse estimée d'environ un facteur 100 et le rayonnement d'énergie se produisant en effet ne pourrait causer complètement la diminution de masse importante ici mise en compte, que si une plus grande période de temps, de plusieurs puissances de 10, était à disposition.

Le matériel empirique a été récemment présenté par Nernst[17] dans une

[16] Meyer37, citation unfound
[17] NERNST 1935.

formulation particulièrement instructive et cette formulation nous rappelle fortement de quelle source notre connaissance des masses stellaires provient. Nous déduisons de manière empirique les masses stellaires à partir des périodes de rotation des étoiles doubles et avec cette façon de procéder la constante gravitationnelle devient essentielle. Nous pouvons donc considérer les masses des étoiles fixes, vieilles et jeunes, comme presque égales en acceptant une variation spatiale de κ pour autant que nous attribuions aux plus jeunes étoiles des tables de Nernst une valeur de κ cent fois plus grandes.

§9. Nerst a pu aussi réaliser, sur base des éléments rassemblés, une définition de l'âge des étoiles dans le cadre de ses tables selon la considération suivante. Il a formulé l'hypothèse selon laquelle la durée de développement de l'étoile simple peut être au moins plus petite d'une puissance de 10 que celle de la voie lactée. Et que, d'après cela, une répartition statistique stationnaire temporellement des différents stades d'évolution dans la voie lactée existe (respectivement dans notre voisinage). Dès lors, chaque étape de développement est représentée dans une fréquence proportionnelle à sa durée.

Nernst découvre ensuite des valeurs relatives de l'âge qui apparaissent jusqu'à neuf fois l'âge actuel du soleil. Ceci est manifestement trop selon les nouvelles représentations. La représentation, selon laquelle l'âge du monde n'est pas fondamentalement plus grand que celui des étoiles simples les plus anciennes, fournit néanmoins une préférence statistique pour les étoiles les plus anciennes ; dans ce cadre nous arriverons sans doute à des résultats quantitativement satisfaisants.

§10. Pourtant, la mesure de temps géologique définie par la radio-activité obtient une certaine incertitude par rapport à sa constance vis à vis du temps élémentaire $\frac{e^2}{mc^3}$, en acceptant une constante de gravitation qui se transforme remarquablement en un intervalle temporel de 10^9 ans. Nous l'avons déjà indiqué dans le **§2**.

Il n'est pas exclu - on ne sait pas grand chose de certain à ce sujet - que la constante de Fermi donnant la mesure de la désintégration β est liée à la constante de gravitation, et qu'elle devrait se transformer en même temps que celle-ci. Au delà de ça, les forces de liaisons nucléaires sont peut-être - encore que ce ne soit absolument pas certain - à considérer comme des conséquences des lois qui régissent la désintégration β. De ces forces de liaison nucléaires dépend néanmoins la demi-vie des rayonnement α et peut-être aussi, comme nous l'avons déjà souligné dans notre travail précédent, dépendent les masses du proton et du neutron.

En tout cas, la situation n'est en aucun cas aussi inquiétante qu'il pourrait apparaître dans ce qui a été dit : le rapport des masses du proton et de l'électron est si petit, par rapport aux nombres $\frac{R}{\Lambda}$ et $\frac{M}{m_P}$ cosmologiquement sans dimension, que certainement aucun changement remarquable temporellement ne soit mis en cause. Et probablement que les forces de liaison nucléaire ne vont pas de paire avec le phénomène β mais plutôt avec l'électron lourd dont l'existence apparaît maintenant certaine [18]. Néanmoins, nous ne considérons pas seulement la construction ultérieure mais bien les fondements de la cosmologie actuellement dans une incertitude remarquable.

Mais dans tous les points essentiels nous voyons le problème cosmologique intimement lié avec les travaux actuels non seulement de l'astronomie mais aussi de la physique. Ceci justifie l'espoir aussi bien à propos de la percée dans la recherche cosmologique qu'en ce qui concerne la fécondité rétro-active de la cosmologie face à la physique pure.

A.4 Jordan 1939 - Bemerkungen zur Kosmologie

To pursue the study of Jordan's work, some translations have been made. This one has been published[1].

Bemerkungen zur Kosmologie[2]
by P. Jordan[3]

The purpose of this study is to develop, roughly and logically, the cosmological theory, which follows when we accept for bases Dirac's principle on the one hand and, on the other hand, the homogeneity of the world (in expansion). It follows (with the principle of energy conservation) a constant growth of matter by production on the model of stars and nebulae explosion.

§1. The cosmological representation sketched in what follows is essentially based on Dirac principle [4], according to which we can interpret the huge di-

[18] La première photographie de Wilson d'une particule de rayon d'altitude qui n'est ni un électron ni un proton a été publiée par Kunze il y a des années Kunze 1933.

[1] Dubois et Füzfa 2020.

[2] Translated by E.-A. Dubois with the helpful collaboration of D. Bertrand, the original article is Jordan 1939a.

[3] Deceased in 1980.

[4] P.A.M Dirac, Nature **139**. S.323, 1001. 1937 Dirac 1937b

mensionless quantity of terrestrial and cosmical physics as functions of the age of the universe. The special interpretation, like Dirac granted to this principle[5] does not seem sufficient to me; then it is preferable to put up for discussion a quite different theory whose mainlines I partly developed in previous publications[6,7].
The learnings from spectroscopy achieved from faraway objects justify the fact of considering the world geometry as Riemannian (with integrable length transmission), and more distant [8], of considering the dimensionless number $\frac{e^2}{hc}$ maybe as a cosmological constant; the length element $\Lambda = \frac{e^2}{m_o c^2} \sim 2 \times 10^{-13} cm$ also stays in a strong relation with the length $\frac{h}{m_o c}$ together with lengths defined by a Cd-spectral-ray or with a Pt-rod.
Besides, we accept that the proton mass m_p is in a constant cosmological relation with the electron mass and that the forces binding the nucleus are cosmological constants. The fact of accepting this reasoning is empirically founded [9]. The functioning of radioactive clocks is in a strong relation with the time-element $\frac{\Lambda}{c}$.
However, the cosmological constancy or inconstancy of beta-forces, is uncertain; the Fermi's constant for beta-decay is perhaps proportional to $\kappa^{\frac{1}{4}}$, where κ is the (relativistic) gravitational constant; the possibility of spontaneous decay probability of the mesotron seems, according to Blackett, visibly proportional to $\kappa^{\frac{1}{2}}$. Nevertheless, this plays no essential role in the following.

§2. Without reference to the size of the length elements (which has only the existence of unstable length measurements), we can enunciate the following astrophysical fundamental constants :

1. $c = 3 \times 10^{10} cm/s^{-1}$
2. $\kappa = \dfrac{8\pi f}{c^2} = 1.87 \times 10^{-27} g^{-1}/cm$
3. $\mu = 10^{-30} g\, cm^{-3}$
4. $\alpha = 1.8 \times 10^{-17} s^{-1}$ [10]
5. $A \cong 10^{10}\text{years} = 3 \times 10^{17} s$

Here, A is the age of the universe, established from radioactive clocks and sustained by some other astrophysical facts and reflections. Hereafter, α is the

[5] DIRAC 1938.
[6] JORDAN 1937.
[7] JORDAN 1938.
[8] P. Jordan Ztschr.f.Phys. (to appear).
[9] (cf. ibid)
[10] Here there is a typo in the original paper, the value $1.8 \times 10^{-7} s^{-1}$ is written.

Hubble's constant, μ the average mass-density of the universe and κ the relativistic gravitational constant. Given that this, hereinafter, (according to Dirac) is not considered as a true constant but as a slowly unstable value, it is essential to accept, in the planetary system, the κ value as approaching the average current value of κ.

From the above-mentioned values, two dimensionless numbers could be built.

$$\alpha A = 5.4 \tag{A.4.1}$$

$$\frac{\alpha}{c\sqrt{\kappa\mu}} = 15 \tag{A.4.2}$$

The fact that these dimensionless numbers are close to 1 makes the fact plausible that simple relations exist. After this, it permits the clear definition of two numbers R and M with length and mass dimension :

$$\begin{cases} R = \dfrac{1}{\sqrt{\kappa\mu}} = 2.5 \times 10^{28} cm = 2.5 \times 10^{10} \text{light-years;} \\ M = \dfrac{1}{\sqrt{\kappa^3\mu}} = 1.3 \times 10^{55} g; \end{cases} \tag{A.4.3}$$

Or, using (A.4.2), without κ (with α instead), we establish :

$$\begin{cases} R \cong \frac{c}{\alpha}, \\ M \cong \mu \dfrac{c^3}{\alpha^3} \cong \mu R^3. \end{cases} \tag{A.4.4}$$

A satisfactory theory must

a) make the relations (A.4.1) and (A.4.2) comprehensible,

b) offer a clear analysis of the numbers (A.4.3) respectively (A.4.4),

c) put in harmony, in a simple way, Hubble's effect with the principle of the non-existence of speed larger than c.

Moreover, the interdiction of exceeding the speed of light is applied to Hubble's redshift, even if we should try to treat the analysis of Hubble's effect as a Doppler effect (which anyway seems to us forced or artificial).
These requirements are met, when we leave (A.4.2) on one side, and take us up to numbers and relations independent of κ, the easiest way with the representation of a Riemannian space with a radius R and a mass M. The radius grows at light speed, and has initially (at time A) a very little value. In the cosmological model suggested by Dirac, the flat infinite space is accepted with

an infinite mass, such as R and M lose their meaning.
However, the relation (A.4.2) need to be interpreted too, which, when we define R and M with (A.4.4), as

$$R \cong \kappa M, \tag{A.4.5}$$

could be expressed as an approximate consensus between the value of the geometrical universe radius and the value of the gravitational universe radius. We interpret this - following a Hass's remark - as the expression of the energy principle written in the form $\frac{\kappa M^2}{R} \sim M$, it means the added potential energies Mc^2 of all material particles are precisely compensated by the negative gravitational energy, so that the whole universe energy stays constant (namely virtually null). In a possible way, maybe it could be appropriate to take also notice of the kinetic energy of the nebulae flux, which will get the same order of magnitude, like the sum of the potential energies.[11] Especially, the matter concentration for the stars, the nebulae[12], makes necessary a more precise conception of the energetic assessment with which, again, the orders of magnitude are unchanged.

§3. If we divide R by the length element Λ - or in the same way, the universe age A by the time element- we find back a value of size around $\gamma \sim 10^{40}$, this will be called in the following shortly as the age of the universe. A division of M by $m_p = 1,6510^{-24} g$ gives, like Eddington and Hass found it, something close to γ^2 ; and with the conclusion of Dirac's principle, it leads to an empirical law - which is not yet theoretically founded- of Nature

$$\frac{M}{m_p} = \left(\frac{R}{\Lambda}\right)^2 ; \tag{A.4.6}$$

or in Hass's new writing

$$Mc \cong h\frac{R^2}{\Lambda^3}. \tag{A.4.7}$$

The surprising conclusions are :

a) M is not constant but grows proportionally to γ^2 ;

b) κ also is not constant, but with (A.4.5), is inversely proportional to γ :

$$\kappa \cong \gamma^{-1}\frac{\Lambda}{m_p}. \tag{A.4.8}$$

[11]This is equivalent to the other statement, that Hubble's flow the current values of μ and κ, are exactly enough to prevent a conditional concentration due to the gravitation of cosmic masses. Gamow and Teller (GAMOW et TELLER 1939) discussed, in an interesting way, the fact that taking into account more precisely the numerical values of the effect of the flux is remarkably stronger than the gravitational effect. However, in our thoughts, it is right to deal only with questions which stay when the numbers of order of magnitude 1 are replaced by 1 in the summarized thought, without taking so fine proportions into account.

[12]Jordan used the world *Nebeln* surely to speak of the galaxies.

This law (A.4.8) has been brought out by Dirac. In an other side, Dirac showed that the hypothesis of a world mass growing could be avoided, nevertheless, we can hold Dirac's principle only at the cost of the hypothesis of an infinitely large universe in volume and mass. In the following, the idea of a world mass temporally growing must be followed to win elements for a future decision. Surely, the hypothesis of a new and constant production of mass in space is disconcerting. Our knowledge about cosmological questions is however currently yet so limited that it could be heuristically useful to conceive the different solutions of the cosmological problem that seem plausible, if possible in a systematic way. Furthermore, the present considerations have nothing more than a heuristic value.

§4. The application of Dirac's principle is, due to the fact that e^2/hc and m_p/m_0 are already noticeably different of 1, linked to important incertitudes. The value $m_p\Lambda^{-3} \cong 10^{14} g/cm^3$ could be estimated as the maximum of the physically possible mass. This order of magnitude is present in atomic nuclei, the well-known Baade and Zwicky's Super-Novae-Theory assign an as large approximative density to the star[13]. Although this density value is much larger than the white dwarf density $\sim 10^5$ or the hydrogen density 1, this difference only lays on factors founded on atomic physics and, consequently, are cosmologically constant. So, it is right to not relate them to γ in the mean of Dirac's principle : we obtain a density of 1 as order of magnitude, when we replace in $m_p\Lambda^{-3}$ the length element by the Bohr's hydrogen radius.
The new dimensionless constants appear now when we compare the radii and the masses of the stars and the spiral nebulae with Λ and m_p[14].

In spite of the difficulties just touched upon, it is certainly possible to judge reliably with respect to the star how to apply Dirac's principle here. The significant differences existing between the different stars types lay on atomic physic factors ; to agree, we can say this :

a) Eddington's theory of lighter stars[15],

b) Kothari's theory of dwarf stars[16] and

c) Zwicky's theory of neutron star[17] with R and M

give as a result a proportionality with $\kappa^{-1/2}$ or $\kappa^{-3/2}$, so

$$R_{St} \sim \gamma^{1/2}; M_{St} \sim \gamma^{3/2}. \tag{A.4.9}$$

[13] Zwicky 1939.
[14] Kothari 1938a.
[15] cf. A.S. Eddington, Der innerre Aufbau der Sterne. Berlin 1928 Eddington 1926.
[16] Kothari 1938b.
[17] cf. ibid

On the other hand, in the spiral nebulae, the application of Dirac's principle is facilitated by the larger similitude of these objects, according to Chandrasekhar and Kothari[18], it seems that

$$R_s \sim \gamma^{3/4}; M_{Sp} \sim \gamma^{7/4}. \tag{A.4.10}$$

The increase of values in question with the age of the universe will not naturally mean the individual growth of the entities, but only the increasing of the values seeming maximal - at the youngest constructions. Possibilities of empirical tests from here are already expressed elsewhere by Zwicky. The fact that in the three cases - stars, spiral nebulae and cosmos - the mass is proportional with $\gamma \times radius$, could be publicly expressed, that the ratio (A.4.5) holds as well for the stars and spiral nebulae as for the universe, atomic physical factors. This is close to the consideration which gives a closer explanation to the growth process of the mass of the universe M. In an Euclidian free-mass space, the spontaneous creation[19] of a spherical mass M_0 of constant density and with a radius R_0 requires none energy, if

$$R_0 = \frac{3}{40\pi}\kappa M_0. \tag{A.4.11}$$

Because, to scatter this sphere entirely against the gravitation, the same energy M_0c^2 would be necessary, that could be represent by these scattered masses. We want to represent ourself the production of cosmic mass necessary by reason of the proportionality between M and γ^2 occurs by the spontaneous creation of simple stars. These ones have, at the beginning, approximately the density $m_p\Lambda^{-3}$, whose the radius and the mass, expressed respectively in elementary unit of length Λ and mass m_p, are of the orders of magnitude of $\gamma^{1/2}$ and $\gamma^{3/2}$. In fact, the rest energy M_0c^2 of a spontaneously dawning star must be balanced only by its own negative gravitational energy. In the neighbourhood of a spontaneous appearing star, the apparition of other stars is facilitated in an energetic point of view ; and, because of the validity of (A.4.5) for the simple star as for the spiral nebula and the cosmos, the energy used for the mass production is balanced in a similar order of magnitude by

a) the gravitation of the simple star,

b) the gravitational interaction inside the dawning spiral nebula and

[18] cf. D.S. Kothari ibid

[19] The author of the present work has decided to use the term *creation* in order to put it echoed with following Bondi and Gold, and Hoyle's models. However, the German word is not *Schöpfung*, nor *Erstellung*, neither *Kreation*. Jordan used the name *Entstehung* which is closer to the translation *emergence*. This has nothing to do with a theological or metaphysical *ex nihilo* creation, but concerns more a producing process from a substratum.

c) the gravitational interaction with the other spiral nebulae.

We will make the link between this hypothesis of spontaneous apparition of spiral nebulae and the empiric fact that it is undeniable to have young and old spiral nebular[20]. Furthermore, it is well suitable with this that the spiral nebulea are empirically composed by simple stars[21], and not by continuously propagating matter. So that the representation from Kant and Laplace's ideas of a star building by an addition of concentration of little masses gravitationally bended don't find empirical base.
The spontaneous creation of a whole star with $\gamma^{3/2}$ - an elementary part in a unique elementary act is surely a representation with a rough exaggeration. Maybe it is the place to indicate in this context Heisenberg's explosion shower, whose reality became little by little likely and, in these cases, happens in normal conditions with a very large number of produced particles by an indivisible act.
Naturally, our own first considerations above-mentioned can not offer any substitute to energetic assessment of stars creation for the missing dynamics for these process, that is why the observational equipment could provide us a vast empirical base, for example the relation to the clusters of stars.

§5. The spatial energy density of light in inter-spiral nebulae space is only of a factor $\sim 10^{-6}$, and the cosmic radiation energy density is only $\sim 10^{-4}$ times more little than μc^2 [22]. These factors could become clearer in an atomic physics context, so that the ratio of radiation and matter are cosmologically constant. We are far away of considering the production of cosmic rays as a side process of the production of cosmological matter ; through which a complementary participation of Baade and Zwicky's Super-Novae process could not be excluded. The estimate apparition rate of a Super-nova per nebula per thousand years , seems to be $\gamma^{1/2}$ super-nova in the universe per time element, in consequence :

- the number of available stars is $\sim \gamma^{1/2}$,
- for all stars, the transition into a Super-Nova probability $\sim \gamma^{-1}$, per time element ;
- and a total radiation production going with $\sim \gamma$, proportional to the cosmic mass.

The superior limit (which can not be defined precisely) of the energies appearing as particles of the cosmic rays, expressed in multiple of m_0c^2 or m_pc^2, is a large

[20] Jordan 1938.
[21] See, for example, E. Hubble, Das Reich der Nebel. Braunschweig 1938 Hubble 1936d
[22] Haas 1934.

number on the other hand, maybe of the order of magnitude of $\gamma^{1/4}$. It is likely that the cosmic ray strength grows without end like the age of the universe.

A.5 Jordan 1947 - Die Herkunft der Sterne

Jordan was also a general public writter. In 1947, he publishes a book on the origin of the stars. Intrigued by his conception of the matter creation, there is a translation of the first chapter of this work.

L'origine des étoiles[1]

P. Jordan

Chapitre 1 : La naissance des étoiles

1. Le principe de Dirac Les théories cosmologiques exprimées à ce jour dans la littérature ont plutôt un caractère déductif fort : elles développent les conclusions mathématiques à partir de lois naturelles choisies comme conditions initiales (comme surtout l'équation du champ de gravitation d'Einstein) et soulignent un modèle cosmologique précis (ou un choix de tels modèles) comme solution possible des équations de départ sur lequel on fonde le raisonnement. Il (le modèle cosmologique) est proche de la réflexion qu'il pourrait promettre une plus grande sécurité, au lieu de cela, précéder de manière inductive et par ailleurs de seulement développer les conclusions qui apparaissent en quelque sorte inévitables à partir des faits expérimentaux. Nous devons être conscients du fait que dans le développement de la cosmologie, des phénomènes et des lois apparaissent, qui ne nous sont pas suffisamment connus par notre propre expérience, et que nous pouvons espérer découvrir seulement à partir de l'observation du cosmos. C'est pourquoi, il apparaît important, dans la tentative d'analyser théoriquement des données expérimentales à ce sujet, pour probablement de tolérer de tels points de vue, dont on peut attendre qu'ils puissent faire l'expérience, par la découverte de phénomènes pas encore connus à ce jour et inattendus, d'aucune limite de leur signification. En conséquence, nous voulons, en nous satisfaisant au début d'une vue d'ensemble globale dans les grandes lignes, utiliser nos observations de dimensions et notre analyse de l'ordre de grandeur comme outil de travail fondamental de notre recherche.

En microphysique, comme chacun sait, un nombre de constantes naturelles sans dimension s'impose à nous, comme l'inverse de la constante de structure

[1] Jordan47

fine de Sommerfeld $\frac{hc}{2\pi c^2} \cong 137$ ou le rapport de masses du proton et de l'électron $\frac{m_p}{m_0} \cong 1838$. Chacun de ces nombres sans dimension nous met face à une obligation : nous voudrions savoir pourquoi il a la valeur empirique existante et non pas une autre - nous sommes convaincus de devoir trouver un sens plus profond mathématico-naturo-légal dans cette valeur numérique. Mais toutes les constantes sans dimension de la nature dans la physique théorique (y compris la géométrie) ramenées jusqu'à présent à des rapports fondamentaux simples (p.e. le rapport de la circonférence et du rayon, ou le rapport de la période d'oscillation d'un pendule et du nombre de même dimension $\sqrt{\frac{g}{long}}$) sont d'ordre de grandeur 1 ; il est donc très surprenant que les particules élémentaires, dont nous nous attendions d'une certaine manière à rencontrer des rapports simples, offrent des valeurs numériques qui ne peuvent être des constantes de la nature simplement explicables. Peut-être est-il fondé que les lois naturelles à la base des particules élémentaires soient en réalité plus complexes que nous l'avions supposé jusqu'il y a peu, le nombre croissant de nouvelles particules élémentaires découvertes récemment a été augmenté par la découverte de plusieurs types de mésons légers. Mais il y a un autre nombre sans dimension, pour lequel il n'y a pas d'explication : le rapport entre l'attraction coulombienne entre un électron et un proton et leur attraction gravitationnelle est d'environ de l'ordre de grandeur 10^{40}.

C'est un mérite d'Eddington d'avoir exigé qu'on ne puisse pas regarder un tel grand nombre sans dimension comme un hasard insensé mais de le considérer comme un fait distinct et compréhensible. Sa tentative de découvrir des fondements mathématico-naturo-légaux pour l'apparition de ces nombres et de nombres semblables, nous la considérons pourtant comme ayant désespérément échoué. Nous voyons la solution de la difficulté dans le principe introduit au départ par Dirac pour un cas bien précis ; d'expliquer des constantes naturelles très grandes (ou très petites) comme n'étant pas en vérité des fonction de l'âge du monde : l'âge du monde aujourd'hui, exprimé en unité de mesure de la microphysique, est lui même un grand nombre sans dimension et de très grands nombres apparaissant par ailleurs peuvent être analysés comme convenant potentialité de l'âge de l'univers, de sorte que seulement des nombres d'ordre de grandeur 1 ou de l'ordre de grandeur des constantes naturelles de la microphysique (libre de gravitation) ne restent seulement comme coefficients. Il faut laisser ouverte la question de savoir si ces constantes naturelles - donc en particulier $\frac{m_p}{m_0}$ et la constante de structure fine - sont à considérer comme de véritables constantes, ou également comme des fonctions de l'âge de l'univers – en quelque sorte logarithmique. Dirac a mis en évidence la possibilité d'une telle instabilité logarithmique à juste titre : une décision empirique serait alors seulement possible si on pouvait mesurer de multiples décompositions dans des nébuleuses spirales très éloignées, ce qui est bien encore peu accessible. Dans une note précédente[2], j'ai cru déceler que, déjà sans prise en considération de la décomposition multiple dans les raies spectrales des atomes avec plus d'un électron, la question de la constance de la constante de structure fine pourrait être testée, mais c'était une erreur. En omettant les effets relativistes (spin inclus) l'équation de Schrödinger d'un atome avec n électrons est

$$-\frac{h^2}{8\pi^2 m_0}\sum_k\left(\frac{\partial^2}{\partial x_k^2}+\frac{\partial^2}{\partial y_k^2}+\frac{\partial^2}{\partial z_k^2}\right)\phi+e^2\left(\frac{1}{2}\sum_{k\neq 1}\frac{1}{r_{kl}}+Z\sum_k\frac{1}{r_k}\right)\phi=W\phi, \tag{A.5.1}$$

par l'introduction de coordonnées de lieu sans dimension

$$x_k=\frac{e^2}{m_0c^2}\xi_k;r_k=\frac{e^2}{m_0c^2}\rho_k \tag{A.5.2}$$

nous obtenons

$$-\frac{1}{2}\sum_k\left(\frac{\partial^2}{\partial\xi_k^2}+\frac{\partial^2}{\partial\eta_k^2}+\frac{\partial^2}{\partial\zeta_k^2}\right)\phi+\left(\frac{1}{2}\sum_{k\neq 1}\frac{1}{\rho_{kl}}+Z\sum_k\frac{1}{\rho_k}\right)\phi=\left(\frac{2ße^2}{hc}\right)^2\frac{W}{m_0c^2}\phi \tag{A.5.3}$$

Il apparaîtrait donc, si des valeurs variables des constantes de structure fine pouvaient apparaître dans les nébuleuses spirales lointaines, une multiplication de toutes les raies spectrales provenant de là (en négligeant des décompositions multiples) autour d'un facteur commun. La présence d'un tel effet ne peut être exclu, mais donnerait comme résultat seulement une dépendance temporelle logarithmique une constante de structure fine dans le cadre des idées développées dans la suite, seulement des corrections légères en dehors des possibilités de mesure. Dès lors, nous ne souscrivons pas à cette possibilité. Dans le cadre de l'application du principe de Dirac, on obtient de grands nombres naturels sans dimension (à éliminer par prudence lors de l'application) par le fait que des nombres d'ordre de grandeur $\sim 10^{10}$ peuvent être liés aussi bien à l'âge du monde qu'avec les plus petites constantes naturelles microphysiques d'après l'état des proportions. Ainsi, si dans la suite nous interprétons l'ordre de grandeur 10^{10} des étoiles fixes contenues dans une nébuleuse spirale moyenne comme une puissance (exposant $\frac{1}{4}$) de l'âge du monde, par contre, l'apparition du même ordre de grandeur dans les désintégration β a un sens complètement autre. La longévité des espèces de mésons s'élève à environ 10^{-6} sec, la longévité du neutron par contre s'élève à 10^4sec, le rapport entre les deux a donc une valeur si grande parce que, comme Nordheim[3] a pu le montrer, il est pour des

[2] JORDAN 1939b.
[3] NORDHEIM 1939.

raisons visiblement théoriques proportionnel avec la 5e puissance de la relation de masse méson-électron.

2. Cosmologie macro-physique Parmi les 6 grandeurs essentielles empiriques de la cosmologie, trois sont définissables par des observations terrestres :

- La vitesse de la lumière c,
- La constante gravitationnelle $\kappa = \frac{8\pi G}{c^2}$,
- L'âge du monde $A = 2, 10^{17}$s.

L'âge du monde serait défini comme âge maximal d'objets naturels connus (Terre, Soleil, météorites, étoiles fixes, nébuleuses spirales) nous donnons la valeur de Paneth connue pour les plus vieilles météorites[4]. La statistique des nébuleuses spirales [5] fournit trois autres grandeurs :

- la constante de Hubble α,
- la densité cosmique moyenne μ,
- le rayon de courbure R.

Ce dernier est empiriquement défini par le fait que l'intervalle des distance r, $r + dr$ des masses à observer n'égale pas $\mu 4\pi r^2 dr$ mais dans une première approche égale

$$dM = \mu 4\pi r^2 dr \left(1 - \frac{r^2}{R^2}\right) \tag{A.5.4}$$

D'après une réflexion géométrique simple déjà connue de Zölner, la suppression de ce facteur correcteur entraînerait que le ciel nocturne ne serait pas noir mais aurait plus ou moins la clarté du disque solaire.

Par ailleurs, α est défini par le fait que les raies spectrales des nébuleuses indiquent un redshift a une distance r,

$$\frac{\Delta\lambda}{\lambda} = \alpha \frac{r}{c} \tag{A.5.5}$$

Pour μ, des valeurs de 10^{-25} jusqu'à $10^{-26} \frac{g}{cm^3}$ furent évaluées autrefois par de Sitter. Aujourd'hui, $\mu = 10^{-30} \frac{g}{cm^3}$ est accepté par de nombreux auteurs, mais par exemple Zwicky[6] tient compte d'une valeur un peu plus grande à

[4]Cependant, les nouvelles idées de F. Houtermans parlent d'une valeur deux fois moins grande.

[5]Les méthodes et les résultats de statistique sur les nébuleuses sont expliqués dans un résumé clair dans HECKMANN 1942

[6]ZWICKY 1939.

savoir $10^{-28}\frac{g}{cm^3}$; cette valeur qui est considérée par Becker[7] comme la plus vraisemblable, convient mieux à nos réflexions.

α, μ, R, doivent être exprimables à partir de fondements dimensionnés c, κ, A ; et les valeurs numériques de manière frappante, sont telles qu'on peut prétendre jusqu'à des facteur d'ordre un :

$$\alpha \cong A^{-1} \tag{A.5.6}$$

$$R \cong cA \tag{A.5.7}$$

$$\mu \cong \frac{1}{\kappa c^2 A^2} \tag{A.5.8}$$

Les relations A.5.4 à A.5.7 permettent une constatation claire : nous nous représentons l'univers comme un espace de Riemann (en choisissant, parmi les différentes constatations exprimées à ce jour, la plus simple la plus claires) avec un rayon de courbure R qui croît en ordre de grandeur à la vitesse de la lumière et qui, au début de l'âge du monde a eu une très petite valeur. L'univers a donc aussi une masse finie de l'ordre de $M \sim \mu R^3$.

En lien avec l'expansion décrite par A.5.7, A.5.8 conduit à une conclusion étrange : la supposition d'une constante temporelle κ et M est impossible. Car dans ce cas, μ devrait être proportionnel à A^{-3} au lieu de A^{-2}. On doit considérer comme une fonction de l'âge du monde au moins une de ces grandeurs k, M, ou même les deux. On ne peut échapper à la conclusion que l'on considère la relation A.5.8 comme fortuite, seulement valable pour la valeur actuelle de A ou R. La relation

$$\kappa M \cong R \tag{A.5.9}$$

ayant la même signification que A.5.8, est triviale dans la théorie de la relativité générale (théorie d'un espace de Riemann fini sans expansion), sous la forme exacte $\kappa M = 4\pi^2 R$. On pourrait toutefois penser qu'en raison de la conservation d'énergie en tout cas M devrait être constante temporellement, mais on ne peut pas, dans la formulation d'un bilan énergétique cosmique, oublier l'énergie gravitationnelle. Si on écrit A.5.9 sous la forme

$$f\frac{M^2}{R} \cong Mc^2 \tag{A.5.10}$$

on peut montrer que la somme des énergies simples de toutes les particules élémentaires du monde est d'ordre de grandeur égal au montant de leur énergie

[7]BECKER 1942.

gravitationnelle mutuelle, et il vient ensuite cette similitude d'ordre de grandeur empirique pour rendre plus de manière hypothétique d'une énergie totale nulle pour l'univers entier[8]. Toutefois Gamow et Teller[9] ont établi que l'énergie cinétique de la fuite des galaxie - qui, manifestement coïncide jusqu'à un facteur presque précisément 1, avec Mc^2 - serait 600 fois plus grande que l'énergie potentielle de la gravitation, cependant, en vérité, les précisions des grandeurs cosmologiques ne peuvent pas suffire pour révéler comme réel un facteur si peu égal à 1. La mise en évidence de ce facteur est liée essentiellement à l'hypothèse $\mu = 10^{-30} \frac{g}{cm^3}$, alors qu'avec $10^{-28} \frac{g}{cm^3}$ l'inexactitude disparaît. Nous arrivons donc à la conclusion qu'au niveau du principe d'énergie une instabilité temporelle quelconque de κ et M est admise, pour autant que la relation A.5.8 permette A.5.9. Il apparaît ensuite le mission de déterminer la loi dépendante du temps de κ. Dirac qui a conçu l'idée d'une fonction du temps cosmologique des constantes de gravitation, fonde l'idée que κ est inversement proportionnel à A ; Dirac s'est écarté de la conclusion de notre hypothèse que M doit être proportionnel à A^2 par l'élaboration d'une cosmologie avec un espace et une masse totale infinis[10].

Si on considère une instabilité temporelle des constantes gravitationnelles, on devra penser naturellement également à une irrégularité spatiale de la valeur de κ. Cependant cette irrégularité peut seulement être complètement négligeables, vu que des fluctuations temporelles de κ devraient apparaître. Mais, fondamentalement, cette variation des constantes de gravitation signifie que pour un traitement déductif de la cosmologie inductive développée ici au moins une généralisation de la théorie de gravitation d'Einstein est nécessaire, laquelle a traité κ comme un champ plutôt que comme une constante. Je crois avoir trouvé les fondements d'une telle généralisation dans la théorie relativiste dite à cinq dimensions ou projective, laquelle fut fondée par Kaluza en 1921, selon les recherches de différents auteurs, amenée à un certain degré de précision par Pauli [11].

3. Cosmologie microphysique En conséquence, il y a 4 constantes de la physique atomique : c, h, κ, $l \cong 2,10^{-13}$cm qui correspondent aux quatre dimensions physiques : distance, temps, masse et température. Elles peuvent

[8]La formation et la signification de l'état d'énergie dans le cadre de la relativité générale a été l'objet de plus longues discussion. Une définition de l'énergie, qui mène à ce que le cosmos fermé possède une énergie totale nulle, a été précédemment défendue par différents auteurs, cf Pauli

[9]GAMOW et TELLER 1939.

[10]DIRAC 1938.

[11]P. Jordan *Gravitationstheorie mit veränderlicher Gravitationaszahl. Physikal. Z.* 1945 (Epreuves). J'ai l'intention de donner un compte rendu complet de cette théorie dans un livre

être utilisées comme fondement à des unités de mesure naturelles pour les quatre dimensions : à côté de l'élément de longueur l et de l'élément de temps $\tau = \frac{1}{c}$ nous obtenons une unité de masse $\frac{h}{lc}$ qui est proche de la masse du méson m_M ($\cong 10^{-1}$ masse du proton m_P). Finalement, nous obtenons à partir de $\kappa T_\epsilon = \frac{hc}{l}$ un élément de température $T_\epsilon = 10^{12}$ Grad, lequel se distingue par le fait que dans un gaz non dégénéré, chaque particule possède d'après son ordre de grandeur une énergie cinétique $m_M c^2$ et qu'un rayonnement noir électromagnétique de cette température atteint une densité d'énergie $m_M \frac{c^2}{l^3}$. Exprimé dans ces unités, nous obtenons pour κ, R et M les relations de Haas-Eddington

$$\kappa \cong \gamma^{-1} \frac{l}{m_M} \tag{A.5.11}$$

$$R \cong \gamma l \tag{A.5.12}$$

$$M \cong \gamma^2 m_M \tag{A.5.13}$$

dans lesquelles γ représente le nombre sans dimension

$$\gamma = 10^{40}. \tag{A.5.14}$$

Ces relations ont été découvertes, avant que l'effet Hubble le soit, elles ont alors donné l'occasion de croire à l'accessibilité d'une constante naturelle non dimensionnée de taille gigantesque (γ). Une telle constante naturelle contredirait néanmoins les réflexions fondamentales ci-dessus : la tentative réalisée par Eddington de considérer une telle valeur numérique sans dimension comme théoriquement concevable ne peut convaincre.

L'idée exprimée par Dirac, comme mentionnée précédemment, est que l'on peut se débarrasser complètement du problème de la taille (γ) d'une constante naturelle sans dimension, si on tient compte que dans A.5.12 la valeur γ qui apparaît n'est absolument pas une constante pour la théorie d'un espace universel en expansion mais une mesure pour l'âge du monde actuel :

$$A \cong \gamma\tau. \tag{A.5.15}$$

Si on tient néanmoins à ce que le γ qui apparaît dans A.5.11 soit semblable au γ de A.5.12, la constante de gravitation sera une fonction de A ou R et la masse M également

$$\kappa \cong \frac{l^2}{Rm_M}; M \cong \frac{R^2 m_M}{l^2}. \tag{A.5.16}$$

Les deux équations A.5.16 sont équivalentes à cause de $R \cong \kappa M$, de sorte que seulement une d'entre elles s'ajoute comme fondamentalement nouvelle aux relations exprimées au **§1** et définit à elle seule l'instabilité temporelle de κ et M tandis que par $R \cong \kappa M$, la proportionnalité temporelle du produit κM a été établie. Le fait que nous supposons par ces réflexions les unités de mesure microphysiques comme constantes, signifie en aucun cas une hypothèse physique mais seulement une définition appropriée. Dans le sens de l'invariance établie dans la théorie de la relativité générale par les transformations de coordonnées, on pourrait évidemment introduire d'autres définitions générales : ainsi que Samburski a proposé d'accepter le rayon du monde comme constant mais une diminution constante de l'élément de longueur (indirecte par la diminution de h), en plus de cela cet auteur n'était pas au clair avec le fait que ces faits ne sont en aucun cas une hypothèse physique appropriée (et une nouvelle explication de l'effet Hubble), mais seulement une nouvelle définition [12] (et certes inappropriée). Il est clair que particulièrement aussi notre supposition d'une vitesse de la lumière c constamment constante n'est en ce sens pas une hypothèse mais une définition.

La mesure du temps pour la préhistoire cosmologique est définie par une désintégration alpha : le rapport connu au sein d'un halo radioactif dans les roches anciennes justifie de manière empirique la conviction que les désintégration alpha bien définies procurent une échelle de temps indépendante du choix des désintégrations alpha spéciales. Des horloges piézoélectriques ne seront pas dans une relation constante avec des horloges alpha-radioactives, si la constante de structure fine est en fait variable, néanmoins cela appartient à des questions plus fines éventuelles de dépendances logarithmiques au temps. Par contre, la vitesse de désintégration d'une désintégration beta doit être considérée comme variable à l'échelle cosmologique lors d'une application correcte du principe de Dirac. La durée de vie des mésons les plus importants s'élève à 10^{-6}s, donc 10^{17} temps élémentaires. Blackett a exprimé, en lien avec les considérations de Dirac sur la constante gravitationnelle, que la durée de vie du méson pourrait être proportionnelle à la racine de l'âge du monde, donc proportionnelle à $\gamma^{\frac{1}{2}} = 10^{20}$ ou $\kappa^{\frac{-1}{2}}$. Une proportion des possibilités de désintégration beta avec $\kappa^{\frac{1}{2}}$ avait déjà été envisagée précédemment par Pauli.

On pourrait considérer comme objection que des précisions quant à l'âge ont pu être exécutées récemment par Hahn sur d'anciens minéraux sur base de la désintégration beta avec des résultats raisonnables. En fait, les écarts qui apparaîtraient des faits ici commentés sont faibles. Considérons une loi de désintégration radioactive

$$\frac{dN}{dt} = \frac{-c}{\sqrt{t}}N \tag{A.5.17}$$

[12] Voir la discussion critique JORDAN 1938

dans laquelle t est A l'âge du monde maintenant. Dès lors, une valeur $t_1 < t$ pourrait être proche de l'âge du monde actuel, à partir de $\gamma = 10^{40}$ nous obtenons donc avec $t' = t - t_1 << t_1$ l'équation de désintégration qui vaut pour le présent

$$\frac{dN}{dt'} = -\lambda N \text{ avec } \lambda = \frac{C}{\sqrt{t_1}}. \quad \text{(A.5.18)}$$

La solution de A.5.17 est clairement

$$N(t) = \text{const } e^{-2Ct^{\frac{1}{2}}} \cong \text{const } e^{-2\lambda t_1} e^{-\lambda t'}. \quad \text{(A.5.19)}$$

Une roche qui se serait formée à l'époque t_0 et serait connue à partir de données empiriques $\frac{N(t_1)}{N(t_0)}$. Dès lors, d'après une formulation exacte de A.5.19,

$$2\lambda t_1 \left[1 - \left(\frac{t_0}{t_1}\right)^{\frac{1}{2}}\right] = \ln \frac{N(t_0)}{N(t_1)}, \quad \text{(A.5.20)}$$

le fait d'accepter une vitesse de désintégration constante au lieu de t_0 une valeur qui s'en écarte t_0* donnerait

$$\lambda t_1 \left[1 - \frac{t_0*}{t_1}\right] = \ln \frac{N(t_0)}{N(t_1)}. \quad \text{(A.5.21)}$$

L'écart pour de si petites valeurs t_0* est le plus grand : on obtient au cas limite $t_0 = 0$ une valeur t_0* qui est accordée par

$$1 - \frac{t_{0*}}{t_1} = 2 \text{ ou } t_0* = -t_1. \quad \text{(A.5.22)}$$

Pour l'âge de la roche $t_1 - t_0$, on obtient donc au lieu de la valeur t_1 la valeur $2t_1$.

La possibilité de tester par des mesures de précision la dépendance temporelle dont il est question des désintégrations β m'a été expliquée plus précisément par Houtermans[13]. Pour un âge global du monde d'environ 3.10^9 ans la perspective existerait déjà d'en comprendre l'effet. Si, par contre, le monde est selon Paneth au moins de 7.10^9ans, alors l'effet est encore en dehors de ce qui peut être vérifié actuellement.

A.6 Jordan 1959 - Zum gegenwärtigen Stand der Diracschen kosmogischen Hypothesen

Jordan never gives up on a cosmological model based on Dirac principle, as it can be seen in the next translation.

[13] HOUTERMANS et JORDAN 1946.

A propos de l'état actuel des hypothèses cosmologiques de Dirac[1]

P. Jordan

Introduction Il y a longtemps, Dirac avait formulé les deux hypothèses suivantes : pendant l'évolution de l'univers :

(1.) la constante de gravitation décroît inversement proportionnellement à l'âge de l'univers

(2.) la masse de l'univers augmente proportionnellement au carré de l'âge de l'univers.

Bien que Dirac lui-même n'ait pas poussé ces hypothèses plus loin (et même abandonné la 2e), l'auteur a quand même consacré des analyses approfondies à ces hypothèses, qui furent également approfondies en partie par d'autres auteurs. De plus, Fisher, Ehlers aussi bien que Dicke[2] ont interprété des idées remarquables concernant la signification géophysique de (A.6.) pendant que Pauli a essentiellement encouragé l'explication de l'interprétation physique des équations du champ débattues par l'auteur.

En 1955, l'état des choses de cette époque fut rassemblé dans la 2e édition de mon livre *Gravitation et Univers*[3]. Indépendamment de mes investigations, Thiry a poursuivi des recherches parallèles. Entre-temps, Fierz[4] a donné une explication parfaitement concluante aux questions qui étaient en débat en poursuivant dans une certaine direction les indications données par Pauli. Si on se réfère aux informations communiquées par Fierz - et il me semble qu'elles sont effectivement convaincantes - il semble que (A.6.) de Dirac n'est plus défendable vu que ni celles vérifiées par l'auteur ni absolument aucune équation du champ qui peuvent être déduites du principe variationnel ne permettent une percée de la conservation de la masse dans une interprétation physique correcte forcément prescrite. Ce point est d'ailleurs aussi important pour les théories mises au point par Hoyle et d'autres auteurs de l'univers stationnaire avec une création continue de matière infime par cm^3 par seconde dans l'espace, cette hypothèse ne peut être exprimée avec un Lagrangien. Dans la suite la question de savoir si (A.6.) de Dirac peut être maintenue, peut être discutée. Une courte explication des résultats de Fierz est un préliminaire. En plus, quelques remarques doivent être formulées, remarques qui se réfèrent aux possibilités d'examens empiriques des hypothèses de Dirac.

[1] JORDAN 1959.
[2] DICKE 1957.
[3] Chez Vieweg-Braunschweig
[4] FIERZ 1956.

Précisions sur le principe variationnel de Fierz Dans les analyses de l'auteur, on confronte au principe variationnel de la théorie de la gravitation usuelle avec $\kappa = \textit{constante}$ un principe variationnel général. Pour le champ vide d'Einstein-Maxwell, le problème variationnel est établi dans une formule courante

$$\begin{cases} \delta \int \left(G - \frac{\kappa}{2c^2} F_{kl} F^{kl} \right) d\tau = 0, \\ d\tau = \sqrt{-g} dx^{(0)} ... dx^{(3)}; \end{cases} \tag{A.6.1}$$

dans le cas de la présence de matière, nous devons ajouter à la fonction de Lagrange celle de la matière de Maxwell-Feldes qui peut être construite à partir du champ d'onde de la matière de façon usuelle.

La formule A.6.1 se généralise par

$$\delta \int \kappa^{\eta} \left(G - \zeta \frac{\kappa_{|j} \kappa^{|j}}{\kappa^2} - \frac{\kappa}{2c^2} F_{kl} F^{kl} \right) d\tau = 0 \tag{A.6.2}$$

avec deux constantes réelles : η et ζ. A propos de ζ, qui doit être grand, environ 10^2 ou plus, pour ne provoquer aucun changement empirique concernant le périhélie de Mercure ou d'autres effets semblables. La valeur de η est sans influence sur de nombreux problèmes mathématiques posés par les équations du champ, les solutions peuvent être transformées - mais fondamentale pour l'interprétation physique de la théorie. Dans mes recherches précédentes $\eta = 1$ est au début entièrement adopté, pourtant dans mon livre, j'ai souligné déjà brièvement que des raisons existent (eut égard à la transformation conforme de Pauli) pour qu'à la place, on prenne $\eta = -1$ comme valeur correcte (pour autant qu'on considère vraiment cette théorie comme pouvant être discutée).

Le résultat de l'analyse de Fierz est maintenant que, en effet, seule la valeur $\eta = -1$ peut être utilisée dans une tentative de justification de l'hypothèse de Dirac d'un scalaire variable κ (encore séparé de l'énoncé, que κ est inversement proportionnel à l'âge de l'univers). Le problème de variation A.6.2 reçoit donc la forme

$$\delta \int \left(\frac{G}{\kappa} - \zeta \frac{\kappa_{|j} \kappa^{|j}}{\kappa^3} - \frac{1}{2c^2} F_{kl} F^{kl} \right) d\tau = 0. \tag{A.6.3}$$

Les raisons invoquées par Fierz, qui me semblent convaincantes, sont les suivantes :

A. Une autre valeur de η conditionnerait une constante diélectrique du vide ϵ_0 dépendante de κ. Ceci a été noté précédemment par Lichnerowicz. Une instabilité cosmologique de la constante de structure fine, qui (l'instabilité) doit correspondre à ϵ_0 variable, est empiriquement inenvisageable depuis que l'effet Hubble a pu être également mesuré à la raie-21cm. Aussi, est théorique la conviction que la constante de structure fine est une véritable constante soutenue par la théorie des particules élémentaires de Heisenberg.

B. Uniquement dans le cas où $\eta = -1$, l'exigence physiquement nécessaire est remplie que les masses ponctuelles (présentées classiquement) se déplacent selon les géodésiques de la métrique g_{kl} (et pas d'une métrique conforme faussée) et que la constante gravitationnelle peut être définie comme la relation (la proportion) d'une masse lourde/inerte.

C. Est équivalente à B. l'exigence que les longueurs d'onde de Compton des particules élémentaires doivent être des constantes spacio-temporelles de sorte que ces longueurs d'onde peuvent être utilisées comme définition de l'élément de longueur ds (la relation constante entre ces longueurs d'onde et le rayon d'hydrogène de Bohr nécessite de nouveau l'évitement de la constante diélectrique du vide variable mentionnée sous A. avec la variabilité qui en découle de la constante de structure fine).

Pour la valeur $\eta = -1$, et uniquement pour celle-ci, les exigences physiques A.,B.,C. sont vérifiées.

Possibilités de tests expérimentaux de la première hypothèse de Dirac par la mesure de précision de la gravitation On peut, peut-être, dans un temps prévisible immédiat tester si (A.6.), la baisse progressive de la constante de gravitation, est fondée, par la mesure. Il faut en effet tenir compte, comme je l'apprends de R. Vieweg, du fait que des mesures absolues de la pesanteur à la surface de la Terre peuvent être rendues possibles dans un avenir proche avec une précision d'au moins 6 décimales et que des mesures relatives peuvent être poussées à une précision de 9 décimales[5]. Les autres méthodes de mesure aussi sont parvenues à la proximité des effets discutés ici. Des mesures de la métrique gravitationnelle permettent déjà de mesurer des variations périodiques de la gravité, qui correspondent à la 9e décimale. Il est dès lors probable qu'une précision suffisante sur la masse peut être atteinte pour décider du changement temporel en progression supposé à la surface de la Terre endéans une période d'environ 10 ans -dès lors on devrait toute fois réaliser, en vue de gagner des résultats convaincants, des mesures à différents endroits largement séparés pour exclure avec certitude des effets locaux.

Dès lors, la mesure d'un certain changement temporel de la gravitation à la surface de la Terre examinerait clairement deux effets dans leur fonctionne-

[5]Tomaschek 1957.

ment additif, à savoir d'abord le changement des constantes de gravitation elles-mêmes et deuxièmement l'effet de l'expansion de la Terre liée à cela qui devrait donner lieu à une diminution supplémentaire de la gravitation par l'augmentation de l'éloignement du centre de la Terre. Ces deux composantes ne devraient pas être très différentes en ordre de grandeur : pour l'accroissement annuel du rayon de la Terre, entrerait en ligne de compte de l'ordre du millimètre à prendre en compte ou bien d'une grandeur relative de 10^{-10}.

Influence d'une instabilité de κ sur la rotation de la Terre On conçoit aisément que l'expansion de la Terre à laquelle il faut s'attendre comme conséquence de la baisse de κ doive donner lieu à un agrandissement du moment d'inertie de la Terre. Les changements de la rotation de la Terre auxquels il faut s'attendre tombent en effet dans l'ordre de grandeur existant empiriquement de l'inconstance de la rotation de la Terre. Néanmoins, les perspectives de pouvoir tester ici l'hypothèse de Dirac sont tout de même malheureusement peu favorables.

La rotation de la Terre, mesurable avec précision par des horloges à quartz, des horloges à l'ammoniaque et des horloges au Césium, indique des changement temporels qui reposent sur des circonstances variables et sont, en partie, bien compréhensibles. Il y a un changement périodique annuel de la vitesse de rotation en raison du fait que le moment de rotation de la Terre se trouve pour une partie de l'ordre de grandeur 10^{-8} dans les systèmes des vents et des mouvements de marées (les deux parties sont du même ordre de grandeur.). En outre, des variations deviennent lentement apériodiques qui représentent environ 1% du changement de la période, c'est-à-dire pour la variation de la durée du jour, l'ordre de grandeur est d'1 milisec par siècle. Une variation lente des courants marins de même que la fonte des pôles pourraient être impliquées en partie dans ces variations de la durée du jour, que l'on peut difficilement déterminer avec précision. Une partie fondamentale, qui apparaît par marée montante, est la transmission de l'impulsion de rotation de la Terre à la Lune ; cette partie a été examinée arithmétiquement, avec le résultat qu'elle peut expliquer de manière satisfaisante : l'agrandissement observable en astronomie de l'impulsion de rotation de la Lune relatif à la Terre, en lien avec les perturbations causées par d'autres planètes, comme il conviendra encore de commenter. Néanmoins, plusieurs auteurs mettent en doute que cette augmentation d'impulsion de la Lune fait véritablement face à une diminution d'impulsion correspondante de la Terre, car il y a des raisons pour supposer que le mouvement de marée de l'atmosphère[6], à la suite d'un effet de résonance déjà examiné par Kelvin,

[6] Spencer-Jones 1956.

corresponde à une compensation fixe de cette baisse d'impulsion de rotation, en raison de l'attraction du Soleil sur la Terre, sous la transformation de la 'trajectoire' d'impulsion de la Terre en impulsion de rotation propre. Vu que, en outre, la variation séculaire du champ magnétique terrestre laisse supposer que la distribution de l'impulsion de rotation de la Terre, sur ses composantes internes et externes, n'est pas exactement constante ; dès lors, d'autres incertitudes apparaissent face à la séparation et à la reconnaissance d'une composante correspondante de l'expansion de la Terre dans la variation de la durée du jour.

La conservation de l'impulsion de rotation dans un problème des deux corps liés gravitationnellement doit conduire à ce que l'écart moyen des deux corps évolue de manière inversement proportionnelle à κ et la période orbitale évolue de manière proportionnelle à κ^{-2} (Cet agrandissement d'écart pourrait être, comme expliqué dans mon livre, d'une importance capitale pour la théorie de l'origine des étoiles doubles et des systèmes planétaires.) L'agrandissement correspondant de la durée de l'année ne peut être saisi astronomiquement. En ce qui concerne la Lune, il apparaît, lorsqu'on accepte la proportionnalité inverse exacte de κ avec l'âge de l'Univers, et celle-ci est fixée égale à 6.10^9ans, une 'accélération' séculaire de $-0,5$". Empiriquement la Lune a une accélération séculaire de +10", celle-ci repose de manière presque équivalent sur des perturbations planétaires (déjà examinées par Laplace) et sur les mouvements des marrées terrestres. La première composante pourrait être précisée au moyen d'un calculateur avec une précision de 10% ; la deuxième partie permet un test de l'hypothèse de Dirac dès lors un test sera à peine possible à partir du mouvement de la Lune.

Une signification de l'hypothèse de Dirac pour la morphologie de la croûte terrestre et de la Lune L'hypothèse, qu'une expansion de la Terre conditionnée par la diminution de κ a déjà eu lieu depuis son apparition (création), offre des bases d'explication pour une série de faits de géographie et de géologie, qui jusqu'à aujourd'hui sont restés en partie inexpliqués ou qui ont été en partie expliqués de manière inaccessible ou peu convaincante. Il en a déjà été question dans mon livre ; pourtant dès maintenant, une large présentation approfondie est disponible - sous l'aide de nouveaux résultats empiriques de même que par l'exploitation de quelques faits auxquels précédemment, on n'a pas fait appel ; il convient de produire à un autre endroit. Les circonstance principales dont il faut tenir compte sont :

A. Des analyses océanographiques (Ewing) ont, depuis peu, rendu célèbres le systèmes des fosses océaniques.

B. Les méthodes de la physique nucléaire de la définition de l'âge ont permis d'obtenir une image claire des périodes pré-cambriennes (celles-ci ont autrefois été inaccessibles en raison de l'absence de fossiles) dont la durée, environ 6 fois plus grande par rapport au temps écoulé depuis le début du Cambrien, a rendu possible une rectification de certaines doctrines traditionnelles qui étaient favorisées par l'ancienne limitation des analyses à une trop petite période géologique : une soi-disant diversité mondiale de périodes de repos et de plissement, qui pourraient encore apparaître de manière soi-disant périodique, ou une soi-disant limitation du plissement des montagnes aux derniers 500 millions d'années. Dans le rapport de J.T. Wilson, R.D. Russel et R. Mc Cann Farquhar[7], se trouve établie une présentation agréablement accessible des conceptions modernes.

C. La présentation d'une Terre en expansion – contrairement à la doctrine traditionnelle d'une contraction - a été, entre temps, fondée par L. Egyed à partir des faits géologiques et géophysiques. En particulier, l'interprétation convaincante de plaques continentales de J. Fischer, qui a été expliquée dans mon livre, a été donnée indépendamment de Egyed, qui calcule de ce fait un augmentation annuelle moyenne du rayon terrestre (depuis le début de la Terre, il y a 4,4 milliards d'années) d'environ 0,6mm. Egyed ne se réfère pas librement à l'hypothèse de Dirac, mais tente une autre explication pour la réalité de l'expansion terrestre envisagée par lui et prouvée empiriquement (un soi-disant état d'instabilité de la Terre qui, depuis le début de la Terre, passe lentement à un état d'équilibre) qui ne peut être satisfaisante.

D. Il convient de citer également la preuve proposée par Dicke selon laquelle la théorie Darwinienne de l'apparition de la Lune ne peut seulement être adaptée à l'hypothèse de Dirac, mais même seulement dans ce lien, la preuve se montre capable d'apprécier tous les points de notre savoir empirique à ce sujet.

Les commentaires nouvellement annoncés de questions géophysiques-géologiques en lien avec la première hypothèse de Dirac traiteront en particulier des points suivants :

1. des fosses océaniques (et leurs conséquences sur des continents),
2. de la structure de la surface de la Terre dans des plaques continentales et bassins océaniques (cf Fischer),
3. de l' apparition des montées de magma , intrusion et volcanisme (cf Binge),

[7] Spencer-Jones 1956.

4. de guirlande d'îles, chaîne de montagnes,

5. de la croissance, pour ainsi dire, des continents,

6. de la proportion climatique du paléozoïque,

7. de la température terrestre dans le pré-cambrien. (cf Dicke)

Vu que, jusque dans une à deux décennies, selon les spécialistes, une analyse imminente des proportions de surface de la Lune devrait être possible, alors parmi les possibles tests de l'hypothèse de Dirac, ceux qui apparaîtront dans une telle analyse méritent de la considération. Ainsi qu'il en a été fait état dans mon livre, les failles de la Lune (acceptées par Dicke) suggèrent l'interprétation que celles-ci sont le résultat d'une expansion très petite de la Lune. En fait, elles ont été interprétées bien avant dans ce sens par quelques auteurs, ceux par qui un réchauffement radioactif fut envisagé comme cause de l'expansion.

Deuxièmement, l'affirmation de Krause, selon laquelle des formations éoliennes existent sur la Lune (érosion par le vent, dépôt éolien), au cas où elle serait confirmée voudrait dire que la Lune doit avoir eu autrefois une atmosphère, ce qui devrait être valable de même comme preuve pour une ancienne valeur plus grande de κ.

Troisièmement, il est à décider de manière définitive à l'avenir si la théorie bien fondée des cratères lunaires en tant que creusés par des corps météoritiques - sa confirmation soutiendrait inévitablement la théorie de Bringe des volcans terrestres par lesquels une preuve des cratères lunaires comme formation produite de manière volcanique sera exclue.

Annexe B

Publications

This appendix contains our publications

B.1 On the diversity of stationary cosmologies in the first half of the twentieth century

Abstract : Before the establishment of the hot Big Bang scenario as the modern paradigm of cosmology, it faced several early competitors : the so-called stationary cosmological models. There were truly plural and independent approaches incorporating cosmic expansion but without time evolution of the total cosmological density, thanks to the inclusion of some processes of continuous matter creation. We distinguish here three different independent motivations leading to a stationary vision of the universe. First, Einstein's concerns on the asymptotic behaviour of gravitation led him to consider continuous matter creation in a recently discovered unpublished work dated of 1931. Second, there is the quest by Dirac and Jordan for a scientific explanation of numerical coincidences in the values of fundamental constants, leading both to a time variation of Newton's constant and spontaneous matter creation. The third one appears in the steady-state theory of Bondi and Gold as the postulate of the Perfect Cosmological Principle according to which the properties of the universe do not depend in any way of the location and the epoch of the observer. Hoyle developed a mathematical model of spontaneous matter creation from a modification of general relativity that should be considered as a direct legacy of Einstein's and Dirac's approaches. Hoyle's model allows obtaining a "*wide cosmological principle*" as an end-product, echoing Bondi and Gold's Perfect Cosmological Principle. Somewhat ironically, many modern key questions in hot Big Bang

cosmology, like dark energy and inflation, can therefore be directly related to the physical motivations of the early stationary cosmologies.

Keywords : steady-state cosmology - large number coincidence - cosmological principle - history of cosmology

B.1.1 Introduction

The current cosmological paradigm consists of an evolving universe : it undergoes global expansion from a primordial, infinitely hot and dense state that Hoyle coined later the "*Big Bang*"[1].

In an expanding universe, the density of matter must decrease by virtue of conservation laws. This is the stumbling block on which the so-called stationary cosmological models built and stood against the "*Big Bang*" approach. The term "*stationary cosmology*" was first coined by F. Hoyle in his famous paper[2]. However, this term has a completely different meaning than what is nowadays referred to stationary space-time. Indeed, the last refers to a manifold with at least one time-like Killing vector, or equivalently that the corresponding metric is not diagonal (in particular $g_{0i} \neq 0$ $i = 1, 2, 3;$) and does not explicitly depends on the time coordinate. While the first, the "*stationary cosmologies*" refers to cosmological models based on the basic assumption that some physical properties of the universe are constants over space and time. In this paper, we choose to follow this convention for historical reasons and we warn the reader about the possible confusion between stationary cosmologies and stationary space-times.

The first relativistic model of the cosmos is due to Einstein[3] and de Sitter built his own model soon afterwards[4]. Einstein's solution took into account the matter content of the universe but added the so-called cosmological constant to the field equations to allow a static space-time. The equilibrium in the model is guaranteed by an exact balance between the radius and the mass of the universe. de Sitter considered a vanishing density of matter in his cosmological model. Despite this apparently physical non-sense, de Sitter's model became, a few years later, the source of considerable interest because it offered a justification for the observations of the redshifts of the spiral nebulae, through the

[1] Hoyle 1951.
[2] Hoyle 1948.
[3] Einstein 1917.
[4] Sitter 1917a.

motion of test particles in de Sitter's space-time. Although cosmic expansion was not manifest in the original writing of de Sitter's metric, Lemaître showed that under an appropriate choice of coordinates, it really was a dynamical cosmological model[5].

In 1922, Friedmann[6] derived the first dynamical cosmological solutions. In his 1927 paper[7], Lemaître found a similar solution that constitutes a compromise between the Einstein's and de Sitter's models and matched it to yet unpublished data presented by Hubble in a seminar that Lemaître has attended, the later even made a numerical estimate of the cosmic expansion rate, which he dubbed, later on[8], "*Hubble's constant*". This estimate, unfortunately based on poor data, lead to a critical underestimation of the age of the cosmos, of about 2 billion years, that Lemaître overcame later on by relying on a positive cosmological constant and an accelerated cosmological expansion[9]. Overall, Lemaître's cosmological picture of the famous "*primeval atom*"[10] stood on a rigorous mathematical model of the expansion of the universe, which started with some primitive condensed state in which quantum laws must have been at play.

Since that time, strong empirical support has emerged in favour of an expanding universe. The first was the observation by Hubble of a linear relation between the redshift and the distance of nearby galaxies[11]. These measurements are commonly interpreted as the manifestation of a dynamical space-time, and more precisely of an expansion of space. As we shall see, this interpretation is also shared by all the stationary cosmologies. Indeed, these models do not deny the dynamics of the universe but yet they are stationary because the matter density remains unchanged on cosmological scales.

Later, Gamow with his student Alpher and other colleagues extended the primitive state envisioned by Lemaître in a series of papers in which they established the link between the expansion of the universe and the formation of atoms and nuclei. They first predicted the existence of a relic electromagnetic radiation from the formation of atoms and then explained the relative abundance of chemical elements observed in the cosmos through the process of

[5] Lemaître 1927.
[6] Friedmann 1922.
[7] Lemaître 1927.
[8] Lemaître 1931c.
[9] Lemaître 1933.
[10] Lemaître 1931b.
[11] Hubble 1929.

primordial nucleosynthesis[12],[13,14,15]). In 1965, Penzias and Wilson measured a signal[16] which can be interpreted as the cosmological microwave background predicted by Gamow and his collaborators. Although Lemaître envisioned the existence of cosmic relics in 1933[17], he thought they were instead related to cosmic rays.

Nowadays, the hot Big Bang scenario of the expanding universe serves as the current paradigm for cosmic history. If it agrees fairly well with many different observations, it must be noticed that these experimental evidences were found several decades after the beginning of modern cosmology as summarized above. History is too often written by the victors and so historical narratives often tend to overlook the unsuccessful competitors : this is the case for stationary cosmologies. Let us note that is is important, of course, to distinguish the context of discovery and the context of logical justification that are not the same.

The aim of this paper is to distinguish three different paths toward stationary cosmology in the first half of the twentieth century, each path having its own physical motivation, which we detail in the next section. The first one is due Einstein himself[18] in an unpublished draft, as was recently discovered by O'Raifeartaigh[19]. Following his investigation of the asymptotic behaviour of gravitation, started in 1917 with his introduction of the cosmological constant, Einstein arrived to the original idea of continuous matter creation. However, Einstein manifestly gave up the idea, but for unmentioned reasons. O'Raifeartaigh et al.[20] suggest that, when Einstein realised that a successful steady-state model necessitated a change to the fields equations, he abandoned the model as too contrived. The second path was opened by Eddington[21] in his attempt for a mathematical explanation of the value of the fine-structure constant which was then somewhat pursued independently by Dirac and Jordan in their works on large numbers coincidences. In particular, we shall show that Jordan also introduced a stationary cosmological model involving spontaneous matter creation. The third path we present is constituted by the work of Bondi and Gold in

[12] Gamow 1946.
[13] Alpher, Bethe et Gamow 1948.
[14] Gamow 1948.
[15] Alpher et Herman 1948.
[16] Penzias et Wilson 1965.
[17] Lemaître 1933.
[18] Einstein 1931a.
[19] O'Raifeartaigh et al. 2014.
[20] Ibid.
[21] Eddington 1931c.

1948[22] which is often wrongly assimilated to the independent work of Hoyle[23] into the "*Hoyle-Bondi-Gold steady state theory*". Indeed, the starting assumption of Bondi and Gold is the Perfect Cosmological Principle according to which the properties of the Universe do not depend neither on the location of the observer nor on the epoch. On his side, Hoyle developed his own mathematical framework as an extension of general relativity implementing spontaneous matter creation to support his stationary vision of the cosmos[24] (see also Kragh[25]). Hoyle's work should therefore be considered as a direct legacy of earlier approaches by Einstein, Dirac and Jordan.

In the conclusion, we will give a synthetic representation of these different motivations of these early stationary cosmologies. We will also emphasise some of their echoes in modern research, which are now developed in the framework of the old competitor of stationary cosmology : the hot Big Bang scenario.

B.1.2 Two premises of steady-state cosmology

In preamble, it must be underlined the difference existing between a static and a stationary cosmological model. The first one has no dynamical process. A static universe remains always exactly the same, identical to itself. The second does not deny a possible dynamical process but remains similar to itself. A stationary universe evolves with time but some observational measures stay constant.

The nomenclature "steady-state" or "stationary" is not used to indicate that these models deny the dynamics of the universe predicted by Lemaître[26] and measured by Hubble[27] ; but, it is a way to dub these cosmological models which postulate an unchanging though expanding universe. Indeed, in these steady-state models cosmic expansion is achieved with a constant expansion rate, making Hubble's parameter a fundamental physical constant. Evolution is, in some sense, still preserved in the dynamics of space-time and somewhat also on the matter content that is continuously created so the matter density stays unchanged.

Einstein's lost paper

In the beginning of the twentieth century, Albert Einstein's theories of special and general relativity allowed the advent of physical cosmology, based on a

[22] Bondi et Gold 1948.
[23] Hoyle 1948.
[24] Ibid.
[25] Kragh 1999.
[26] Lemaître 1927.
[27] Hubble 1929.

rigorous background and equations linking together space, time, matter and energy. Immediately after having published his relativistic equations of the gravitational field[28], Einstein applied, in 1917, his new theory to the universe as a whole as he was questioning the asymptotic behaviour of gravitation and the associated boundary conditions[29].

Einstein elegantly eluded the problem of choosing appropriate boundary conditions for space-time by considering the geometry of the 3-sphere which does not require specifying asymptotic behaviour nor boundary conditions. However, to ensure the hydrostatic equilibrium of the cosmos, Einstein had to extend his field equation through the introduction of a new cosmological constant term to the field equations, then denoted $\lambda g_{\mu\nu}$, where $g_{\mu\nu}$ is the metric tensor encoding the geometry of space-time and λ is the cosmological constant (nowadays denoted by Λ), which can be interpreted as an intrinsic scalar curvature of space-time (i.e. the scalar curvature in vacuum). Following Einstein : "*that term is necessary only for the purpose of making possible a quasi-static distribution of matter, as required by the fact of the small velocities of the stars*"[30]. This new cosmological constant term introduced a new long-ranged force into relativistic gravitation while being compatible with the fundamentals of general relativity : the equivalence principle and general covariance. The cosmological constant term $\lambda g_{\mu\nu}$ later turned out as a non trivial adding to general relativity, glimpsing at interplay between quantum mechanics and gravitation. However, Einstein mention the possibility of doing without it, especially in his letter to Weyl[31] and discarded it in 1931[32].

In 2014, O'Raifeartaigh et al. published some papers[33] concerning a recently discovered attempt by Einstein on a steady state model of universe, a work left unfinished and abandoned before publication[34]. With the help of some experts, the unknown manuscript was dated as likely written in early 1931. The content of this draft has been studied in several papers, including[35].

The following discussion is based directly from the original work of Einstein in 1931, and not on later translation. Let us start with Einstein's equations

$$\left(R_{ik} - \frac{1}{2}g_{ik}R\right) - \lambda g_{ik} = \kappa T_{ik} \tag{B.1.1}$$

[28] Einstein 1916.
[29] Einstein 1917.
[30] Ibid., p.432 of the translation.
[31] Einstein 1923.
[32] Einstein 1931b.
[33] O'Raifeartaigh et al. 2014, and references therein.
[34] Einstein 1931a.
[35] Nussbaumer 2018.

where g_{ik} is the metric tensor, R_{ik} the Ricci tensor, T_{ik} the stress-energy tensor, R the scalar curvature, $\kappa = 8\pi G/c^2$ and λ is Einstein's notation for the cosmological constant.
The so-called Einstein universe, first derived in 1917[36], corresponds to a static space-time with identical 3-sphere as spatial slices, in which matter has a constant density ρ in time and space. Unfortunately, this solution is well known to be unstable, since the balance is achieved through a fine-tuning of the value of the cosmological constant λ to compensate for the homogeneous density ρ. Since the former must rigorously be constant to be compatible with the fundamentals of general relativity while the later is not rigorously constant in the cosmos, the equilibrium is unstable under density perturbations[37]. Although Hubble's results showed a Doppler effect proportional with the distance, which were interpreted by Lemaître as inherited from cosmic expansion, a dynamical property of space-time, Einstein described such a model in his 1931 draft as unacceptable, without detailing his reasons.

Einstein suggested instead a different model, compatible with Hubble's observations but with a mean density of matter that was constant over time. The mathematics and notations below are those of Einstein's draft[38] that we chose to reproduce identically here in order to follow Einstein's steps to a stationary cosmology. Using the metric[39]

$$ds^2 = c^2 dt^2 - e^{\alpha t}\left(dx_1^2 + dx_2^2 + dx_3^2\right) \tag{B.1.2}$$

and modelling cosmic matter through the stress-energy tensor of pressure-less perfect fluid

$$T^{\mu\nu} = \rho u^{\mu} u^{\nu}$$

where u^{μ} is the fluid 4-velocity which takes the form, once expressed in the fluid co-moving frame, $u^1 = u^2 = u^3 = 0$ and $u^4 = \frac{1}{c}\cdot$ Einstein first noted the following, incorrect, field equations (temporal then spatial) :

$$\frac{3}{4}\alpha^2 - \lambda c^2 = \kappa\rho c^2, \tag{B.1.3}$$

$$\frac{9}{4}\alpha^2 + \lambda c^2 = 0 \tag{B.1.4}$$

[36] EINSTEIN 1917.

[37] This instability can be deduced from the classification of dynamical cosmologies by A. Friedmann in 1922 where the author has shown that Einstein's universe sits at an unstable equilibrium point (see Fig. 125-1 of Friedmann's 1922 article (FRIEDMANN 1922)). On this subject, Eddington's book (EDDINGTON 1930a) could also be quoted.

[38] EINSTEIN 1931a.

[39] In Einstein's draft, a crossing-out can be seen, he corrected only one on the two expressions of the metric to have a signature (+, -, -, -). Furthermore, it is interesting to notice that Einstein uses covariant coordinates and not the expected contravariant ones.

where the first[40] and second equations of the above set correspond to the spatial and temporal components of Eqs.(B.1.1), respectively.

The system Eqs.(B.1.4-B.1.3) imposes $\alpha^2 = \frac{\kappa c^2}{3}\rho$, leading to a constant density. Einstein then argues that, considering a finite physical volume, particles are constantly escaping because of the cosmic dynamics and therefore there should exist some process of continuous creation of matter in order to keep the total matter density constant. Einstein even proposed that this new particles should emerge from space as this last is not empty due to the presence of the cosmological constant λ. Einstein therefore associated the cosmological constant term λ with the creation of matter as, we will see, Hoyle did in[41].

Unfortunately, the first equation (B.1.4) was wrong and Einstein corrected himself and found [42]

$$-\frac{3}{4}\alpha^2 + \lambda c^2 = 0, \tag{B.1.5}$$

which, together with Eq.(B.1.3) implies that the matter density is indeed constant but trivially zero. The solution of the problem posed by Einstein in this draft was in fact de Sitter's vacuum solution[43], once expressed in the coordinates found by Lemaître[44].

Before O'Raifeartaigh's work, it was not known that Einstein himself had considered the possibility of a universe fitted with a continuous process of matter creation, a central feature of the future steady-state models. Einstein's draft should therefore be considered as the first attempt to build a stationary cosmo-

[40] We also reproduce the mistake in the physical dimensions of the right hand side of Eq.(B.1.3).

[41] HOYLE 1948.

[42] The mistake probably lies in the computation of the Ricci spatial component $R_{ii} = \frac{-3\alpha^2 e^{\alpha t}}{4c^2}$ and consequently of the curvature scalar $R = \frac{3\alpha^2}{c^2}$.

[43] If we write down the metric Eq.(B.1.2) as

$$ds^2 = c^2dt^2 - e^{2\alpha ct}\left(dr^2 + r^2 d\Omega^2\right)$$

with $d\Omega^2 = r^2(d\theta^2 + \sin^2(\theta)d\varphi^2)$ the solid angle element, one can obtain the so-called Schwarzschild-de Sitter metric

$$ds^2 = \left(1-\alpha^2\bar{r}^2\right)c^2d\bar{t}^2 - \left(1-\alpha^2\bar{r}^2\right)^{-1}d\bar{r}^2 - \bar{r}^2(d\theta^2 + \sin^2(\theta)d\varphi^2)$$

through the following change of coordinates

$$\begin{aligned} r &= \bar{r}\left(1-\alpha^2\bar{r}^2\right)^{-1/2}e^{-\alpha c\bar{t}} \\ ct &= c\bar{t} + \frac{1}{2\alpha}\log\left(1-\alpha^2\bar{r}^2\right) \end{aligned} \tag{B.1.6}$$

the angular coordinates being unchanged. It could be noticed that in 1917 de Sitter did not already work in the Schwarzschild-de Sitter coordinates (SITTER 1917b)

[44] LEMAÎTRE 1925, and references therein.

logical model within general relativity, through Einstein's proposal to preserve a constant matter density. Shortly afterwards, Einstein published a paper on the cosmological problem of the general theory of relativity in which he finally discards both of his 1917 cosmological contributions : (i) his static universe, on the grounds that it is unstable and (ii) the cosmological constant term λ since, according to him, Hubble's observations could be accounted for more naturally in general relativity without invoking this term. This last paper[45], sometimes known as the Friedmann-Einstein model, constitutes the first occasion on which Albert Einstein formally abandoned the cosmological constant term, never to re-instate it afterwards. An analysis and first English translation of the paper has recently been provided by O'Raifeartaigh and McCann[46]. Another contemporary paper by Einstein is his famous work with de Sitter[47], in which they estimated the pressure-less matter density of the expanding universe and discussed other measurable quantities in cosmology. However, there seems to us that there are no connections to make between this published paper[48] and the unpublished one[49].

Fundamental Constants, Large Numbers Hypothesis and the Stationary Universe

Several reflections on the fundamental constants of physics also led some physicists to envision a stationary view of the universe.

On the edge of the nineteenth century, Planck[50] build his famous set of absolute, natural, physical units, by combinations of c the speed of light, h Planck's constant, G Newton's gravitational constant, e and m_e the charge and the mass of the electron respectively. For example, Planck defined a unit of time as $t_P = \sqrt{\frac{G\hbar}{c^5}} \simeq 10^{-43}s$ while Dirac and other authors worked with a unit of atomic time[51] : $\frac{e^2}{m_e c^3}$. These absolute units, build on fundamental physical constants, can then be combined to construct some dimensionless numbers.

In *Relativity theory of Protons and Electrons*[52], Eddington worked on "*a*

[45] Einstein 1931b.
[46] O'Raifeartaigh et McCann 2014.
[47] Einstein et Sitter 1932.
[48] Ibid.
[49] Einstein 1931a.
[50] Planck 1899.
[51] The unit of measure of the electron charge e in the cgs system was the statcoulomb which has units $\left[cm^{\frac{3}{2}}g^{\frac{1}{2}}s^{-1}\right]$.
[52] Eddington 1936.

series of investigations in the borderland between relativity theory and quantum theory. (p.V) ". He noticed a multiple appearance of the natural number[53] 136, and in his opinion "*there are no arbitrary constants left in the scale of relation of natural phenomena.*" (*ibid* p.V). Eddington has set a theory for calculating each of them purely deductively, especially from his theory of the Clifford algebra. He thereafter set a line of research of other authors that will search for explanation of the precise values of these constants.

Dirac[54] noticed that the age of the universe, estimated at that time around 2×10^9 years, once expressed in atomic units, gives 10^{39}, and dubbed this large number the *epoch* t. Furthermore, the ratio γ of the strength of the electrostatic (Coulombian) force over the one of the gravitational (Newtonian) attraction between the electron and the proton in the fundamental system of the hydrogen atom has also a value around 10^{39}. These large numbers, γ and t, appear in two a priori independent physical contexts so that they should rely on two fundamentally different justifications. However, such a coincidence that the ratio γ is roughly equal to the epoch t might reveal a deep connexion in nature between cosmology and the atomic theory. Following Dirac, this closeness of two independent and such large numbers cannot be purely coincidental, so γ must change as the universe evolves, if this coincidence reflects a deeper yet unknown physical law that is forever valid. In addition, the other large dimensionless numbers occurring in nature can all be expressed as simple powers of the -non dimensional- epoch t. For example, the ratio between the mass of the observable universe and the one of a proton, which is equal to 10^{78}, could be seen as t^2. As a consequence, Dirac noted that the number of protons and neutrons have to increase as t^2 and the Newtonian gravitational constant has to be inversely proportional to t.

In 1938, Dirac suggested a new starting point for cosmology based on the following principle, that will be later on called Dirac's principle : "*Any two of the very large dimensionless numbers in nature can be connected by very simple mathematical relation*"[55]. He then suggested a new view of the cosmos assuming an infinite space filled with an infinite amount of matter. If Dirac mentioned the possibility of spontaneous creation or annihilation of matter, he soon rejected it because it does not fit with any idea in theoretical physics : "*There is no experimental justification for this assumption since a spontaneous creation or annihilation of protons and neutrons sufficiently large to alter appreciably*

[53]Eddington first worked on the number 136, later he rather focused on 137, this change is due to the improvement of the measure of e and m_e

[54]DIRAC 1937b.

[55]DIRAC 1938, p.201.

the law (3) $[a(t) \propto t^{1/3}]$ *would still be much too small to be detected in the laboratory. However, such a spontaneous creation or annihilation of matter is so difficult to fit in with our present theoretical ideas in physics as not to be worth considering, unless a definite need for it should appear, which has not happened so far, since we can build up a quite consistent theory of cosmology without it*"(*ibid* p.204) Dirac therefore abandoned for a while this model because of the success of the standard paradigm, before he went back to it in the seventies[56,57,58].

However, while Dirac gave up this stationary cosmology, someone else soon took it over : P. Jordan developed a completely new cosmological model in a series of papers[59,60,61,62]. His motivation was simple : it is useful for science to explore every possible solution, in particular for what concerns the cosmological problem, and not stay confined to what currently appears as good explanations.

Jordan, in 1937[63], followed the way opened by Dirac and Eddington. He made the calculation[64] to express the epoch in atomic unity, arriving at the huge value of 10^{41}. He suggested that we can neglect the daily growth of the epoch, because this represents only a modest increase of 10^{27} time atomic units per day. Jordan saw in his study of the large dimensionless constants a possibility to reconcile astronomical and atomic physics. He pursued this idea in several papers[65,66,67]. Jordan based his model (i) on the principle previously introduced by Dirac that the dimensionless numbers in nature must be mathematically related and (ii) on the unity and coherence of the universe (while still incorporating cosmic expansion).

This cosmology requires a creation of some matter content, which Jordan considered to be stars, a small amount of matter compared to the vastness of matter in the universe. However, Jordan's explanation of spontaneous creation of *simple stars* is based on energy arguments and remains quite vague : the net

[56] DIRAC 1973b.
[57] DIRAC 1973a.
[58] DIRAC 1974.
[59] JORDAN 1937.
[60] JORDAN 1938.
[61] JORDAN 1939a.
[62] JORDAN 1948.
[63] JORDAN 1937.
[64] Jordan assumed a universe ten times older than Dirac's one, compatible with the age of the Earth known by geological data at that time. The difference in their calculations must reside in the precision of e and m.
[65] JORDAN 1938.
[66] JORDAN 1939a.
[67] JORDAN 1948.

energy cost of the creation of a star is null because the negative gravitational binding energy is balanced by the rest energy. "*In an Euclidian free-mass space, the spontaneous creation of a spherical mass M_0 of constant density and with a radius R_0 requires none energy, if $R_0 = \frac{3}{40\pi}\kappa M_0$. Because, to scatter this sphere entirely against the gravitation, the same energy M_0c^2 would be necessary, that could be represent by these scattered masses.*"[68,69]

In 1949, Max Born drew attention of the scientific community to Jordan's works via a publication in Nature[70]. Paul Couderc in his work[71], studied Jordan in the appendix and classified it as a heterodox theory. Indeed, it must be recognized that Jordan's approach was quite heuristic and not supported rigorously by some mathematical background, at the opposite of Hoyle's approach in 1948.

B.1.3 The Twofold Steady-State Cosmology

One cannot study the stationary cosmologies without considering two different approaches that are nowadays referenced collectively as the Bondi-Gold-Hoyle steady-state model. H. Bondi, T. Gold and F. Hoyle spent a lot of time together during the WWII and, according to Mitton[72] and Livio[73], the idea of an evolving but unchanging universe pried into their mind after their vision of the movie *Dead of Night*[74]. This lead these authors to two separate publications. Indeed, in the fifth release of 1948 MNRAS, you can find these two papers : *The Steady-State theory of the expanding universe* by H. Bondi and T. Gold[75], submitted in July, followed by *A New model for the expanding universe* by F. Hoyle[76], submitted in August. These two articles presented crossed references and commentaries ; however the two approaches expressed are quite different epistemologically and mathematically.

First of all, it must be noticed that Bondi and Gold quoted Hoyle's paper. As for him, Hoyle introduced his paper revealing that its general idea came from a discussion with Gold and thanking Bondi for his comments and their many discussions. At first sight, one could wonder why they did not publish together. The reason is that, beyond their friendship, the ideas defended by

[68] Jordan 1939a, p.69.
[69] This citation is extracted from our translation of Jordan's works from the German.
[70] Jordan 1949.
[71] Couderc 1950.
[72] Mitton 2011.
[73] Livio 2013.
[74] Balcon 1945.
[75] Bondi et Gold 1948.
[76] Hoyle 1948.

the authors are, if not opposite, at least very different, and drove them to a kind of schism. In a later discussion[77], Hoyle is questioned by Schlegel about the Perfect Cosmological Principle, an idea developed by Bondi and Gold[78] ; Hoyle's answer is welcomed by this self-explanatory comment by Bondi : "*We do not all agree*"[79]. This disagreement is also underlined by Kragh[80,81]. The assimilation of theses two articles in a unique Steady-State Theory proposed by these three authors is a misunderstanding or, at least, a late assimilation and short-cut.

The Perfect Cosmological Principle of Bondi and Gold

Bondi and Gold suggested a heuristic approach based on the *Perfect Cosmological Principle* : "*As the physical laws can not be assumed to be independent of the structure of the universe, and as conversely the structure of the universe depends on the physical laws, it follows that there may be a stable position.*"[82]. The Perfect Cosmological Principle therefore shares the conviction of the universality principle according to which the laws of physics do not change with time and stay everywhere valid. To assume this principle lead Gold and Bondi to a universe that is homogeneous and stationary at large scales. As the they noted, the opposite hypothesis led to an untenable situation "*We do not claim that this principle must be true, but we say that if it does not hold, one's choice of the variability of the physical laws becomes so wide that cosmology is no longer a science.*"[83]. With this assumption, one can be fully confident about the universality of observations and the validity of their interpretations.

Considering a homogeneous and stable universe, one cannot reject the observed large-scale motions, so that the model must incorporate cosmic expansion. "*It is clear that an expanding universe can only be stationary if matter is continuously created within it.*"[84]. Such an expanding universe can be stationary only if you allow continuous creation of matter. Bondi and Gold then mentioned that such a model must be described by a de Sitter metric, as Einstein did in his draft in 1931 and as Hoyle did in his 1948 paper. Indeed, de Sitter's geometry written in the coordinates of Eq.(B.1.2) incorporates cosmic expansion at a constant expansion rate α but requires a constant total density. Since matter density decreases due to cosmic expansion, this must be compensated by conti-

[77] HOYLE et NARLIKAR 1963.
[78] BONDI et GOLD 1948.
[79] HOYLE et NARLIKAR 1963, p.340.
[80] KRAGH 1999, pp. 179-186.
[81] KRAGH 2015a.
[82] BONDI et GOLD 1948, p.254.
[83] Ibid., p. 255.
[84] Ibid., p. 255.

nuous creation of matter. As mentioned by Einstein and de Sitter in 1932[85], only matter density and cosmic expansion rate were considered as observables at that time, therefore de Sitter's geometry was unavoidable to implement the perfect cosmological principle.

Bondi and Gold then suggested some observational tests, even if they claim the creation process is too faint to be measured. They gave an estimation of the rate of matter creation of about $10^{-43}g$ per second per cm^3, corresponding to one new atom of hydrogen per cubic metre per 3×10^5 years.[86]. Bondi and Gold also considered the physical process of creation, but in a very qualitative way without a mathematical formulation. Their model was not formulated within the context of general relativity, because Bondi and Gold questioned the assumption that general relativity was valid on cosmic scales. However, they noted that the process of matter creation implies a privileged direction along the time dimension as described in Weyl's causal postulate. Hoyle will implement this mathematically in his theory. The authors were confident in the possibility of finding a mathematical formulation for their model in the context of field theory but they said "*we have no hesitation in rejecting Hoyle's theory, although it is the first and at the moment only field theory formulation of the hypothesis of continuous creation of matter.*"[87]. This rejection is especially due to the insertion by Hoyle of non-uniformities.

It could be noticed how confusing is this formulation of the perfect cosmological principle. It seems that Bondi and Gold do not make the distinction between the physical laws and there solutions. It is now completely accepted that if equations are symmetric, the solution, resolving of a break of symmetry, cannot be. Bondi and Gold developed an essay without a formal mathematical model and it is something that could be desired by modern readers.

Hoyle's mathematical approach to stationary cosmology

Hoyle's model[88] was based on the line of thought initiated by Jeans[89] and Dirac[90] and developed the idea of a continuous creation of matter for which Hoyle offered a mathematical formulation. After a study of Newtonian universes, he then turned to the framework of general relativity and, after some

[85] Einstein et Sitter 1932.
[86] Bondi et Gold 1948, p.266.
[87] Ibid., p.269.
[88] Hoyle 1948.
[89] Jeans 1928.
[90] Dirac 1937b.

general considerations, worked with the following line element[91] :

$$ds^2 = c^2dt^2 - a^2(t)dl^2, \tag{B.1.7}$$

where $dl^2 = (dx^1)^2 + (dx^2)^2 + (dx^3)^2$ is the elementary length of flat Euclidean space. Following the standard procedure, Hoyle wrote down the non-vanishing Christoffel symbols and components of the Ricci tensor, as well as the scalar curvature. Then he chose to "*diverge from the usual procedure*" to introduce a new mathematical term in Einstein's equation. This term will describe the process of continuous matter creation.

Indeed, Hoyle added a space-time four-vector field C_μ whose norm is fixed along time-like geodesics :

$$C_\mu = 3\aleph(1, 0, 0, 0), \tag{B.1.8}$$

where $\aleph$ is a constant. This vector C_μ has vanishing spatial components for symmetry reasons and compatibility with the chosen metric. Then, Hoyle constructed a symmetrical tensor $C_{\mu\nu}$ by covariant differentiation of the four-vector field,

$$C_{\mu\nu} = \nabla_\nu C_\mu. \tag{B.1.9}$$

Given the above-mentioned symmetries, this "*creation*" tensor $C_{\mu\nu}$ counts only three non-zero components :

$$C_{ii} = -3\frac{\aleph}{c}a\dot{a} \; ; \; i = 1, 2, 3. \tag{B.1.10}$$

Hoyle then introduced the following *modification* of the Einstein field equations :

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + C_{\mu\nu} = -\kappa T_{\mu\nu}. \tag{B.1.11}$$

Doing this, the stress-energy tensor $T_{\mu\nu}$ is not conserved anymore. Indeed, from the second Bianchi identity, we have :

$$\nabla_\mu \left(R^{\mu\nu} - \frac{1}{2}g^{\mu\nu}R \right) = 0.$$

Then we find that the creation tensor is the source of the production of new particles :

$$\nabla_\mu T^{\mu\nu} = -\frac{1}{\kappa}\nabla_\mu C^{\mu\nu} = -\frac{1}{\kappa}g^{\alpha\nu}\nabla_\mu\nabla_\alpha C^\mu. \tag{B.1.12}$$

One can see that, if $\aleph = 0$, we find back an Einstein-de Sitter universe for a pressure-less matter universe with varying ρ, while, here, ρ is constant. As

[91]In what follows, we have corrected some notations used by Hoyle.

$\nabla_\mu T^{\mu\nu} \neq 0$, the stress-energy tensor is not conserved and the matter geodesics will be modified, C_μ acting like a long-ranged force. Therefore, in Hoyle's theory, one expects the free fall of matter particles to be affected by this new long-ranged force on cosmological distances. Exploring the observable constraints of this phenomenological property would be a significant and interesting work which goes beyond the scope of the present paper.

Comparing the equations (B.1.1) and (B.1.11), one can notice a similarity between the cosmological constant term and the creation tensor. In 1951, Mc Crea[92] included the creation tensor $C_{\mu\nu}$ directly into the total stress-energy tensor on the right-hand side of Einstein equations so that their form stayed unchanged. Thereby, he rightly claimed there is no net creation of matter since the total stress-energy tensor is conserved, due to the second Bianchi identity. However, this yields some coupling between usual matter and a source of usual matter, given by $C_{\mu\nu}$, and so there is indeed no conservation of the number of usual matter particles.

It is important to notice that Hoyle put the term $C^{\mu\nu}$ responsible of the creation of matter on the left hand side of his modified Einstein equations, as a modification of the geometry in the field equations. This approach is similar to Einstein's one in 1917, with his introduction of the cosmological constant term, with the important difference that the modification brought by Hoyle does have an impact on matter conservation while this is not the case for the cosmological constant term. Matter conservation laws are the same whatever the value of the cosmological constant while matter conservation laws must include the creation term in Hoyle's approach. Yet both approaches by Einstein in 1917 and Hoyle in 1948 consisted of modifying the way space-time is curved by matter to account for cosmological considerations.

In addition, Hoyle's model allows matter creation without introducing any violation of the fundamental laws of covariance and the equivalence principle. Gravity is still described through only one metric in the Levi-Civita connection, so that the total stress-energy and Einstein's tensors are conserved. Matter creation can be seen as the result of some interaction between usual matter and some invisible sector through the term $C_{\mu\nu}$. In Hoyle version of the Steady-State Theory[93], this sector is modeled in cosmology by some frozen vector field Eq.(B.1.8).

In the metric chosen by Hoyle, the modified Einstein field equations become

[92] McCrea 1951.
[93] Hoyle 1948.

(temporal equation first, then the spatial one) :

$$3\dot{a}^2 = \kappa\rho c^4 a^2 \cdot \tag{B.1.13}$$

$$2a\ddot{a} + \dot{a}^2 - 3\aleph c a\dot{a} \quad = \quad 0 \tag{B.1.14}$$

It is possible to show that this set of equations has a first integral that takes the form of a Bernouilli equation. The general solution is

$$a(t) = \left(C_1 + C_2 e^{\frac{3}{2}\aleph ct}\right)^{\frac{2}{3}} \tag{B.1.15}$$

The particular solution given by Hoyle, supposing $\dfrac{\dot{a}}{a} = \aleph c$ at $t = 0$, is

$$\begin{cases} \frac{3}{4}\aleph ct = \tanh^{-1}\left(\frac{2\dot{a}}{a\aleph c} - 1\right) - \tanh^{-1}(2\alpha - 1), \text{ if } \alpha < 1, \\ \frac{3}{4}\aleph ct = \coth^{-1}\left(\frac{2\dot{a}}{a\aleph c} - 1\right) - \coth^{-1}(2\alpha - 1), \text{ if } \alpha > 1. \end{cases} \tag{B.1.16}$$

Isolating $\frac{\dot{a}}{a} = d(\log(a))/dt$ in (B.1.16), it becomes easy to develop these expressions to have the general solution. For the first equation of (B.1.16), $-\dfrac{a}{c}C_1 = \dfrac{1}{2}e^{\frac{3}{2}D-C}$ and $-\dfrac{3c}{a}C_2 = \dfrac{1}{2}e^{\frac{3}{2}D+C}$ where $C = \tanh^{-1}(2\alpha - 1)$ and D is an integration constant.

It is interesting to notice that the general solution (B.1.15) of Hoyle's model only reduces to de Sitter space-time and a constant Hubble parameter for this particular choice of initial conditions Eq.(B.1.16) (or $C_1 = 0$ in (B.1.15)) or, equivalently, $a \to 0$ if $t \to -\infty$. This is the only choice allowing both constant density and Hubble parameter, since if $a \to a_{-\infty} \neq 0$ when $t \to -\infty$, one finds a solution with varying density and Hubble parameter. Hoyle's steady-state cosmological model is therefore a consequence of a modification of gravity and a particular choice of initial conditions to guarantee the constancy of H_0 as was considered by many at that time.

Hoyle came to this conclusion : "*It is only through the creation of matter that an expanding universe can be consistent with conservation of mass within the observable universe*"]p.379]Hoyle48. In standard cosmology, based on general relativity, it is the stress-energy tensor that is conserved through the conservation laws $\nabla_\mu T^{\mu\nu} = 0$. Hoyle instead requires that it is the *mass* that is conserved all along cosmic expansion, which is very different : mass is a global quantity[94] while stress-energy is a local one. To ensure this conservation of mass during cosmic expansion, Hoyle has modified Einstein's general relativity but in such a way that there are still conservation laws, but only for the total

[94] BLANCHET, SPALLICCI et WHITING 2011.

stress-energy tensor $T_{\mu\nu} + \frac{1}{\kappa}C_{\mu\nu}$. In addition, the matter creation process must exactly balance the decrease of matter density due to cosmic expansion, which imposes some symmetries to the vector field C_μ.

McCrea[95] suggested a satisfactory description of the consequences of the creation hypothesis may nevertheless be obtained without any modification of Einstein's equations. The creation tensor $C_{\mu\nu}$ is absorbed in the stress-energy tensor.

Hoyle's model has an infinite past and an infinite future, it also satisfied the wide (or, in Bondi and Gold's wording, the perfect) cosmological principle. However, this is a consequence of his development when it was the starting hypothesis of the Bondi-Gold model. Hoyle's stationary model emerges from a modification of general relativity that still incorporates conservation laws but for an extended definition of the matter content of the universe. Therefore, Hoyle's approach is also reminiscent of the one made by Einstein in 1917, when the father of general relativity introduced his famous cosmological constant.

B.1.4 Conclusion

In parallel with the development of the hot Big Bang cosmological model, some other theorists, including Einstein, Dirac, Jordan and later on Bondi, Gold and Hoyle, explored the idea of a stationary universe. Although their motivations were quite different, they all finally came to the need for a process of continuous matter creation.

Einstein attempted a steady-state model, apparently in early 1931, by questioning the nature of gravity and exploring the possibilities offered by his equations. He however quickly abandoned the idea when he realized his approach led to a trivial solution with vanishing density and that a successful approach would require an alteration to the field equations. This 1931 approach was similar to the reasoning that led him to introduce the famous cosmological constant term in his 1917 paper. Dirac and Jordan's approaches followed original work of Eddington in 1936[96] who tried to explain the numerical coincidences between atomic physics and astronomy. Finally, what is usually referenced as steady-state theory actually comes from two distinct models of Hoyle on the one hand, and of Bondi and Gold on the other. The first model by Hoyle can be seen as a link between the exploration of the nature of gravity by Einstein and Dirac's investigation on large numbers. For the second, the motivation is purely phi-

[95] McCrea 1951.
[96] Eddington 1936.

losophical : Bondi and Gold wanted to save the space and time invariance of the physical laws. These different motivations behind stationary cosmology are summarized in (Fig. B.1).

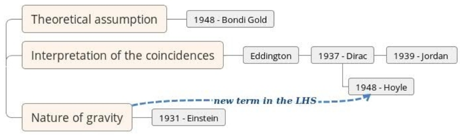

Figure B.1: Three ways to stationary cosmology

In the first half of the twentieth century, the so-called Big Bang model and the steady-state theory emerged as candidates for the status of paradigm of physical cosmology. Even though strong evidence in support of the Big Bang model eventually emerged, notably through the detection of the cosmic microwave background in 1965, the stationary cosmological models, though empirically discarded still are of interest through their underlying epistemological questions and their physical process and mathematical tools that are still in use today. Remarkable examples are the use of de Sitter in inflationary cosmology, and spontaneous creation coupling terms which are currently used in the description of coupled dark energy-dark matter models[97,98,99].

In the last decades, the hot Big Bang scenario has been extended to account for many new observations (galaxy rotation curves, relative height and angular size of the acoustic peaks in the CMB, baryon acoustic oscillations, distance measurements of type Ia supernovae, galaxy clustering, etc.) and to solve the horizon and flatness problems. This leads to the notion of extending matter content by adding new ingredients of dark matter and dark energy to which ordinary matter could directly couple, which would imply its non-conservation during cosmic expansion as with matter creation processes in steady-state cosmology.

The later developments of physical cosmology in the XXth century eventually settled the hot Big Bang scenario as the paradigm of describing the Universe at large, while stationary cosmologies were progressively abandoned, yet not completely. There is large literature detailing the scientific reasons behind the emergence of the current paradigm at the detriment of stationary cosmologies, and a good starting point is certainly the books by Kragh[100] and

[97] Amendola et Tsujikawa 2010.
[98] Perez et al. 2014.
[99] Copeland, Sami et Tsujikawa 2006.
[100] Kragh 1999.

Longair[101] and references therein.

Quite interestingly, many key investigations of modern cosmology already appeared in the very first stationary cosmologies, as we presented here. One can actually relate the pioneering works on stationary cosmologies to four important modern research areas that have interconnections : equivalence principle, modified gravity, cosmological principle and the origin of ordinary matter in the universe. First, Dirac and Jordan's approaches considered the variation of fundamental physical constants which leads to violation of the equivalence principle. Indeed, since those constants are involved into the binding energies of objects, any such change in the physical constants will result in a variation of inertial or gravitational masses and non-universality of free fall. In addition, a space-time variation of fundamental constants must be described by consistent field theory, such as Jordan-Fierz-Brans-Dicke tensor-scalar gravity[102,103,104,105]. Therefore, the approach of stationary cosmologies by Dirac and Jordan finally lead to question the equivalence principle and to formulate extensions of general relativity. Second, Einstein's and Hoyle's starting point was a modification of general relativity that incorporates spontaneous matter creation and from which it is possible to derive a stationary cosmological model as a particular solution. This particular case is actually de Sitter solution in which the cosmological singularity is retrieved asymptotically in the past, as in modern models of eternal inflation[106]. Third, Bondi and Gold's approach to stationary cosmology is related to the debate on the cosmological principle, although nowadays it is focused today on the feedback of large-scale inhomogeneities on the background cosmic expansion. Finally, all the approaches to stationary cosmologies that we described here imply spontaneous matter creation and therefore question the origin of ordinary matter in the universe. This is still an open question at the heart of several research areas including particle creation during inflationary processes, baryo- and leptogenesis, dark matter creation from radiation, etc.[107,108,109,110]).

Although these four research areas have been widely active in the last four decades for tackling several cosmological problems of the hot Big Bang para-

[101] Longair 2006.
[102] Jordan 1949.
[103] Jordan 1959.
[104] Fierz 1956.
[105] Brans et Dicke 1961.
[106] Aguirre et Gratton 2003.
[107] Allahverdi et al. 2010.
[108] Martin, Ringeval et Vennin 2015.
[109] Martin, Ringeval et Vennin 2016.
[110] Clesse et García-Bellido 2015.

digm, it is interesting to see how these ideas also emerged originally in attempts to build stationary cosmologies. Today, we know how modifications of gravity, violation of the equivalence principle[111,112] and departures from the cosmological principle are well constrained[113,114].

However, the processes at work to make the universe stationary, like the creation of matter needed to compensate the decrease of density from cosmic expansion, are also expected to be very faint. It could interesting for future work to examine how Hoyle's modification of gravity for stationary cosmology and the related phenomenological consequences presented here are constrained by modern observations. It is also interesting to notice that several of the original authors pursued their investigations around stationary cosmology for decades. Dirac came back to the implications of the large number hypothesis on cosmology in 1973[115,116,117]. Jordan further developed alternative theories of gravity in five dimensions[118] and investigate geological and planetological evidence in favour of a variation of Newton's constant[119]. Hoyle never abandoned stationary cosmology and continue to improve his mathematical model and its phenomenological consequences[120,121,122].

The deep origin of stationary cosmologies is clearly not motivated by the quest for cosmological models avoiding Big Bang singularity, rooted in philosophical assumptions against the implications of the existence of such a singularity or in new observations. At the opposite, stationary cosmologies appeared at a time where the Big Bang scenario was not favoured as it is today and were based on a study of the consequences of fundamental principles framing all physics. And, despite of the opposition of these two cosmological visions, the evolutionary against the stationary one, they actually share common motivations and applications. The current cosmological paradigm strongly benefits from these early investigations with profound physical motivations, which should therefore not be considered as mere historical curiosities or misguided ways.

[111] TANABASHI et AL. 2018, and references therein.
[112] ADE et al. 2016b.
[113] ADE et al. 2016c.
[114] ADE et al. 2016a.
[115] DIRAC 1973b.
[116] DIRAC 1973a.
[117] Ibid.
[118] JORDAN 1948.
[119] JORDAN 1959.
[120] HOYLE et NARLIKAR 1964b.
[121] HOYLE et WICKRAMASINGHE 1967.
[122] HOYLE, BURBIDGE et NARLIKAR 1993.

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B.2 Comments on P. Jordan's cosmological model

Abstract : We analyse the original cosmology of P. Jordan through his 1939 key paper entitled *"Bemerkungen zur Kosmologie"* or *"Comments on cosmology"*. In this almost forgotten work, the author introduced a model of dynamical cosmology with spontaneous creation of matter, based on the Large Numbers study, initiated by Eddington and further developed by Dirac. Jordan's will to explore heuristically all possible cosmological models in order to be prepared in case of surprising future astronomical data is very compelling in this article. Since we think it is wise to learn from our predecessors and from the unsuccessful theories that were later left behind, the present article also offers an overview of Jordan's work during the 1930s through the analysis of a series of some of his other original pieces. An English translation of Jordan's key paper can be found in the appendix.

Keywords : History of cosmology - Large Numbers hypothesis - Static universe

Introduction

During the thirties, Pascual Jordan, already famous for his work in quantum mechanics, turned to cosmology. The context of this study switch was particular. When Eddington published studies of the fine structure constant, Dirac postulated his Large Numbers hypothesis, which principle led to the variation of fundamental constants as G and the creation of matter. We will detail this more thoroughly in the first section. Moreover, cosmology was a newborn science and, even with Hubble's results[1], dynamical and static models used to compete against each other. As Jordan's model could have been considered to be stationary, in the second section we will compare static and steady state models developed in the thirties.

After this contextual setting, Jordan's 1939 paper,[2], here studied, will be exposed in Jordan's perspective and development, in the third section. Indeed, this work seems to be the closure of an exploration phase, leading Jordan to work on the empirical consequences of his model.

Then, in the fourth section, we will address three engaging points of Jordan's work : his system of units, the variation of the gravitational constant and

[1] HUBBLE 1929.
[2] JORDAN 1939a.

the specification of the created matter.

Jordan's cosmological model did not make it as a breakthrough, nor was it even well diffused at the time. Yet, in 1949, Max Born invited Jordan to present and publish his work in English in *Nature*. This publication will be discussed in the fifth and last section.

After his 1930s work, Jordan pursued the study of his model. However, hereby, we chose to only focus on the first phase of Jordan's work, more centred on cosmology. For more information about Jordan's geological observational consequences see[3] or[4]. More extensive review on variations of constants shall be found in[5] in French or in[6] in English, or more recently in[7].

B.2.1 Large Numbers study

Eddington worked on the fundamental meaning hidden in the fine structure constant $\alpha = \frac{2\pi e^2}{hc}$, where e is the charge of the electron[8]. This number also calls upon Planck's constant h and the speed of light c; Eddington saw in α an opportunity to harmonize quantum and relativistic theories[9],[10]. Using Clifford algebras to describe the wave function of two interacting electric charges, he witnessed the emergence of the number 137, which is equal to the inverse of α[11]. This part of Eddington's work is often associated with numerology, yet we must underline that it opened the way for Large Numbers hypothesis, study of coincidences and Dirac principle.

First, in 1937, in a short letter to *Nature* Editors[12], Dirac expressed the age of the universe in atomic units and found a dimensionless large number, the so-called epoch, about 10^{39}. He noted that the ratio between Coulombian and gravitational forces between a proton and an electron is about 10^{39} and the

[3] KRAGH 2015b.
[4] KRAGH 2016.
[5] UZAN et LEHOUCQ 2005.
[6] UZAN 2011.
[7] KRAGH 2019.
[8] SOMMERFELD 1916.
[9] EDDINGTON 1931c.
[10] EDDINGTON 1936.
[11] We would like to point out that Eddington originally arrived at the result 136 and disregarded the data : "*The experimental value of* $\frac{hc}{2\pi e^2}$ *is* 137. *According to the theory proposed in this paper it should be the integer* 136" (EDDINGTON 1929). Thereupon, he found the value 137 in his theory : "*I appear to have made such a mistake, and the new prediction is* 137." (EDDINGTON 1930b)
[12] DIRAC 1937b.

ratio between the mass of the universe and of a proton is about 10^{78}, roughly the square of 10^{39}. Too improbable to be a coincidence, Dirac wrote :

> "This suggests that the above-mentioned large numbers are to be regarded, not as constants, but as simply functions of our present epoch, expressed in atomic units."[a]
>
> [a]Ibid., p.323.

So the ratio of the two forces must evolve with time and the mass of the universe, expressed in units of proton mass, must increase as the square of the time. This leads to consider variable constants and a process of matter creation.

Quickly after this article, Dirac built a consistent cosmological model based on his 1937 hypothesis[13]. In this new piece, would be laid down what is currently known as Dirac principle :

> "Any two of the very large dimensionless numbers occurring in Nature are connected by a simple mathematical relation, in which the coefficients are of the order of magnitude unity."[a]
>
> [a]Ibid., p.201.

Dirac introduced a development to establish the law of recession of spiral nebulae, which we quote as galaxies, in the frame of the Large Numbers hypothesis. The distance between two galaxies could be expressed in atomic units and becomes a dimensionless number $f(t)$. Working in a system where $c = 1$, the time the light needs to go from one galaxy to the other is also $f(t)$. So, if light is emitted with a period of δt, it will be received with a period of $\delta t + f(t + \delta t) - f(t)$. Knowing that, the redshift, the change in period per unit period, is namely $\dot{f}(t)$. And, defining Hubble constant as the redshift per unit distance, it appears $H = \frac{\dot{f}(t)}{f(t)}$.
Considering the average density of the universe, with galaxies flying away from each other, it could be established that $\rho \propto f(t)^{-3}$. But, on the other hand, Hubble's constant and average density could be made dimensionless, so with the Large Numbers hypothesis, there is a simple relation between them $\rho \propto H$. So, solving $f(t)^{-3} \propto \frac{f'(t)}{f(t)}$, Dirac arrived to the law for the rate of recession of galaxies $f(t) \propto t^{\frac{1}{3}}$[14] and the velocities of recession are not constant, but vary $\propto t^{\frac{-2}{3}}$.

Dirac also studied the curvature of hyper-surfaces defined by a constant time, denoted t-space. Without considering local irregularities, the curvature

[13] DIRAC 1938.

[14] By comparison, in Einstein- de Sitter model, with null pressure, $f(t) \propto t^{\frac{2}{3}}$; a universe of radiation goes with $f(t) \propto t^{\frac{1}{2}}$ and de Sitter model has $f(t) \propto \exp(t)$

of three dimensional space, with t fixed, must be constant. This curvature, k, could be positive, null or negative. It is easy to rule out the positive k case. Indeed, if k is positive, the hyper-surface is closed and contains a finite mass. This finite total mass divided by the mass of the proton gives a large dimensionless number which is a constant. That is in direct contradiction with the large numbers hypothesis. Considering a curvature negative, the same reasoning could be applied to a sphere with radius equal to the radius of curvature. Thus, only the flat t-spaces could satisfy the Large Numbers hypothesis.

The space time could be divided in flat t-spaces and a satisfactory theory of cosmology can be built. Of course, this model required process of spontaneous matter creation (or annihilation). As other cosmological models are consistent with data and do not demand a such exotic process, Dirac temporarily gave up[15] on his attempt at a cosmological model. Moreover, the contemporary models, such as Lemaître's one[16], were satisfying.

Pleading the scientific curiosity and the importance of considering a maximum of theoretical possibilities, Pascual Jordan developed his own cosmological model. Seeing the fine structure constant as a translation of a link between quantum and relativistic theories, developing the ideas of variable constants and of matter creation ; he could be considered in perfect continuity with Eddington and Dirac.

B.2.2 Static versus steady universes

Posing the foundations of cosmology, Einstein had in mind a static universe. This could be seen as a product of Copernician principle : humanity did not rise in a specific space-time configuration of the universe ; the world is static. Einstein built a cylindrical cosmological model[17,18]. Naturally, at that time, the conception of the universe came down to our only galaxy, the Milky Way. Quickly, dynamical cosmological models were conceived e.g.[19],[20] or[21]. In parallel, the rising efficiency of telescopes led to identify other, external, galaxies and to determine a relation between their distance and their velocity,[22], which could be interpreted as a motion at the universe scale. Accordingly, the universe

[15] During the seventies, Dirac came back to his Large Numbers hypothesis and suggested the study of two kinds of matter creation processes (Dirac 1973a), (Dirac 1973b) and (Dirac 1974).

[16] Lemaître 1927.

[17] It is a cylindrical universe with S^3 spatial hyper-surfaces.

[18] Einstein 1917.

[19] Sitter 1917b.

[20] Friedmann 1922.

[21] Lemaître 1927.

[22] Hubble 1929.

was dynamic.

No more static model of the universe could be built, but still, the universe could be steady, or in a steady state. Even if the universe evolves ,a constant will remain or a certain mathematical relation will be conserved. Recently, O'Raifeartaigh discovered that Einstein may have been the first to consider this kind of model[23]. Indeed, in 1931, Albert Einstein worked on a draft about a steady universe[24]. In this attempt, Einstein considered a constant density of matter in the universe. Unfortunately, this density tended to be null. The aborted Einstein's steady universe was, in fact, the empty de Sitter's universe.

Dirac's model, presented in 1938, could be called steady state, even if it was a pure product of the large numbers analysis. Indeed, by preserving the Dirac principle through time, Dirac's model entailed some kind of steadiness.

As for Jordan, he built a cosmological model without any steady state consideration. Yet, his universe is also a steady one. The most acclaimed steady model was presented in 1948 by Hoyle[25]. A comparison of Jordan's and Hoyle's versions was published in a Nature publication, later discussed in the fifth section.

For a further study of the difference between static and steady state universes, and the diversity of their motivations, we invite you to refer to our previous article[26].

B.2.3 Jordan's work

Referring to Eddington's and Dirac's works, Pascual Jordan suggested his own model, which he developed in several articles, mainly in[27],[28] and[29]. As the last one is the most accomplished of this period, we decided to introduce Jordan's cosmological model through the translation of Jordan's *"Bemerkungen zur Kosmologie"* : *"Comments on cosmology"*[30]. After this theoretical research, Jordan dedicated his cosmological work to the experimental and observational aspects, in astrophysics and geophysics. H. Kragh preferred to divide Jordan's cosmological career not in two, theoretical and then observational, but in three,

[23] O'RAIFEARTAIGH et al. 2014.
[24] EINSTEIN 1931a.
[25] HOYLE 1948.
[26] DUBOIS et FÜZFA 2019.
[27] JORDAN 1937.
[28] JORDAN 1938.
[29] JORDAN 1939a.
[30] Ibid.

intuitive, deductive and then devoted to the consequences[31].

Jordan's progression is quite similar to Dirac's one[32]. First, both of them made themselves known with their work in quantum mechanics. Secondly, they both shifted to cosmology via Eddington's numerical work. Eventually, none of them both has been remembered for their cosmological works, in spite of how long they worked on this subject.

As evidence that Jordan's cosmology was not well received, we have taken two mixed reviews on, expressed during the fifties. In 1950, Paul Couderc classified Jordan's model as heterodox, the same way he did Hoyle's, Lyttleton's, Bondi and Gold's, and Milne's[33]. Couderc highlighted the work accomplished but, unfortunately, did not find a scientific value in it. Later, in a review of Jordan's *Schwerkraft und Weltall*[34], McCrea acknowledged the pedagogical qualities of Jordan's introduction to Riemann-Einstein theory, wishing this book would be used as an introductory text for students. However, McCrea was not convinced by Jordan's ideas on cosmology, as Jordan failed to find a global mathematical treatment for his ideas[35]

B.2.4 Walk in Jordan's paper

The article *Bemerkungen zur Kosmologie*, written as a synthesis of cosmological ideas during the thirties, is quite self sufficient. We chose to give a deeper commentary on three important points. First, we will consider the system of units used by Jordan, which was exclusively built from cosmological constants and permits to consider cosmology as a complete field of science, without any requirement of links with quantum mechanics. Secondly, we will analyse the variation of G that Jordan developed, in parallel with the static universe suggested by Sambursky. Finally, we will characterize the matter spontaneously created in Jordan's model. Indeed, he considered creation of stars with a specific mass-radius ratio, thereupon these stars turned out to be compact objects.

System of units in Jordan's work

Five numbers characterized the cosmological knowledge at the time : c, the velocity of light ; κ encoding the gravitational constraint from general relativistic

[31] Kragh 2016.
[32] Kragh 2015b.
[33] Couderc 1950.
[34] Jordan 1952.
[35] McCrea 1953.

theory ; μ, the average mass density of the universe ; α, Hubble's constant[36] ; and A, the age of the universe.

From these five values, Jordan built two dimensionless numbers $\alpha.A$ and $\frac{\alpha}{c\sqrt{\kappa\mu}}$, both of them are in the order of one. This results from Jordan's choice of units, given the characteristic sizes of the cosmological problem. Actually, from the five characteristic constants, Jordan brought out a mass-element $\frac{1}{\sqrt{\kappa\mu}}$ and time-element A. This approach is similar to Planck's in quantum mechanics in 1899[37], when he defined his, now illustrious, system of natural units. Thus, Jordan built a purely gravitational and cosmological system of units without any link to quantum mechanics (through Planck constant) nor to statistical mechanics (through Boltzmann constant). Furthermore, in his system, the cosmological constant emerges also as purely cosmical $\Lambda \simeq \dfrac{3\alpha^2}{c^2}$.

Variation of the gravitational constant

We value expounding Samuel Sambursky's approach as examined by Jordan. What Sambursky wrote[38] is worth to be scrutinised in this paper, since Jordan was the only other author to quote him [39].

For Sambursky, the homogeneous spatial distribution of nebulae indicated that the universe is static. To retain a constant radius of the universe, the radius of the electron and the other universal lengths have to shrink with time.

> "The dynamics of expansion are transferred into the dimensions of atomistic phenomena."[a].
>
> [a]SAMBURSKY 1937, p.335.

Since there are two universal lengths, $\frac{e^2}{mc^2}$ and $\frac{\hbar}{mc}$, whose ratio is the fine structure constant, usually denoted α ; and assuming that α and c are constant, then h ought to decrease with time and e^2 diminish at the same rate as h does. Therefore, Sambursky suggested a static universe with h decreasing, equivalent to an expanding universe with a constant value of h.

Thereby, Sambursky somehow explained the measurement of redshift. By preserving the Planck-Einstein relation $\varepsilon = h\nu$, it becomes manifest that the

[36]To be consistent with Jordan's piece in the Appendix, in this paragraph, the authors chose to keep the original notation α for Hubble's constant, usually α is the fine structure constant and Hubble's constant is written H or H_0

[37]PLANCK 1899.

[38]SAMBURSKY 1937.

[39]Except Sambursky himself in his following work (SAMBURSKY et SCHIFFER 1938).

old stars emitted light when h was larger, so the frequency ν was smaller and was transmitted to us without undergoing any change. Thus, the observations interpreted as a redshift of the emitted light is no more than the true frequency of emission, evidence of the variability of h.

Sambursky propounded a value for $\dot{h}$ of $-1,03 \times 10^{-43}$ erg[40], working with an expansion speed, based on Ten Bruggencate's work[41], of a value of 486 $\frac{\text{km}}{\text{s Mpc}}$. S. Sambursky rejected the idea of a complete linear shrinkage and suggested that h should vanish asymptotically for $t = \infty$. By posing $h = h_0 \exp(-kt)$, the ratio[42] $\dfrac{\dot{h}}{h} = -k$ enables to evaluate the Hubble factor.

From a strictly dimensional point of view, G can be written as $G = \frac{2\pi e^2}{M^2 mc^2} \dot{h}$. And so, it can be witnessed that

$$\frac{GMm}{e^2} = \frac{2\pi \dot{h}}{Mc^2}.$$

Noting that, it becomes obvious that the relation of the gravitational energy of the hydrogen atom to its Coulombian energy (the left hand of the equality) could be expressed by the rest energy of the atom and $\dot{h}$. So, G is not a constant anymore, it is proportional to $e^2 h$ which decreases as h^2, since e^2 behaves like h. And, as the creation of stars and stellar systems is determined by the product GM (where M is the mass of the system), the masses of the stars that arose back in time must be smaller given that G was greater.

As Sambursky's ideas have been delineated, here comes the time to go back to Jordan's paper and his reaction to Sambursky's work. Since[43], P. Jordan is echoing Sambursky's approach. In Jordan's heuristic interest, Sambursky's procedure is completely acceptable. Going back and forth between the expanding universe with constant h and the static universe with variable h is always possible. However, Jordan regretted that Sambursky's idea led to abandon the clear relation between the element of length and the standard measure, like the Platinum rod.

Jordan displayed a new way to reach the variability of G. As $\kappa \cong \frac{R}{M}$ from (eq. 5) and because R divided by the element of length, Λ, is equal to γ, the epoch[44], and with M divided by m_p, the proton mass, is γ^2; it could

[40] That is equivalent to $-1,03 \times 10^{-36}$ J.

[41] Bruggencate 1936.

[42] Pay attention, in the original paper, the minus symbol is missing.

[43] Jordan 1938.

[44] Since (Dirac 1937b), the epoch γ is a dimensionless number defined as the age of the universe divided by a time unit, in most case the atomic time.

be written that $\kappa \cong \gamma^{-1}\frac{\Lambda}{m_p}$. The relativistic gravitational constant κ is not constant anymore but shrinks as the inverse power law of the epoch and so does G [45].

Spontaneous creation of compact objects

A direct consequence of Jordan's assumptions was the spontaneous creation of matter. As observations showed older and younger stars, he deduced that the matter emerges directly in the form of stars. To keep the total energy of the universe, Jordan suggested that the created matter equilibrates its rest energy with its gravitational potential energy.

$$\text{Rest energy} + \text{gravitational potential energy} = 0$$
$$M_\bigstar c^2 - \frac{3}{5}\frac{GM_\bigstar^2}{R_\bigstar} = 0$$
$$R_\bigstar = \frac{3}{40\pi}\kappa M_\bigstar$$

Such created stars were characterised by $\dfrac{R_\bigstar}{M_\bigstar} = \dfrac{3\kappa}{40\pi}$.

This result was based upon the gravitational binding energy in Newtonian gravity $U = \dfrac{3GM^2}{5R}$, which is the energy to provide to destroy a gravitationally bound system, under the assumption that it is a spherical mass of homogeneous density. Jordan's idea was to equal the rest energy (Mc^2) with the gravitational binding energy. Unfortunately, this gravitational binding energy in the strong field regime of general relativity, *id est* of compact objects, is still an open question nowadays. Jordan concealed his use of a Newtonian concept while working in relativity.

Moreover, Jordan came to the creation of stellar objects with a certain ratio between their mass and their radius, without any condition of their order of magnitude. With a modern eye, the compactness[46] of these created stars could be computed. These stars have a compactness of $\dfrac{5}{3}$, making them not luminous at all since their compactness is larger than the one of black holes[47]. In some way, Jordan developed a model of creation of black holes, which foreshadowed primordial black holes in cosmology.

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[45] Jordan preferred the notation f for the Newtonian gravitational constant.

[46] In current notation, compactness is defined as $\Xi = \dfrac{GM}{c^2R} = \dfrac{R_s}{2R} \simeq \dfrac{R_s}{R}$, where R_s the Schwarzschild radius. With this convention, the compactness of a black hole is 0.5 and of a neutron star is 0.1.

[47] GOURGOULHON 2004.

The absence of comment from Jordan on the mechanism of this creation process is regrettable. Indeed, he established the relation between the mass and the radius of a possible created star without explaining the creation in itself.

B.2.5 Publication in Nature

In 1948, two articles published in the *Monthly Notices of the Royal Astronomical Society* suggested a cosmological model with matter creation. There was the birth of the Steady State Theory. In the first founding paper, due to H. Bondi and T.Gold[48], the idea is to enlarge the cosmological principle. This is the idea that the universe, at large scale, is homogeneous and isotropic. This hypothesis is needed to permit the study of the universe as a whole. Bondi and Gold suggested to strengthen this hypothesis, adding a constancy regarding to time. This is known as the perfect cosmological principle. In their work, there is a direct reference to Eddington's work and a more subtle to Dirac : "*A further point to be mentioned in relations to the stationary property of the universe is the coincidence of numbers pointed out by Eddington*[49]*. Two non-dimensional numbers which can be constructed from observation are both found to be of the order* 10^{39}.[50]" They granted the paternity of the study of large numbers to Eddington but, referencing the epoch 10^{39}, there is a clear link to Dirac works.

On the other hand, Hoyle, in the second founding paper of steady-state theory[51], developed a steady-state theory on a more mathematical basis. He suggested a modification of Einstein's equations, $R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R+C_{\mu\nu}=-\kappa T_{\mu\nu}$[52]. By adding the creation tensor, $C_{\mu\nu}$ in the left hand side of the equation, Hoyle's model is very similar to one with a cosmological constant. For a further details on his model, the reader could see[53]. Hoyle arrived to the perfect cosmological principle as a consequence of his modification. Hoyle made a tiny mention of Dirac's work :"*More recently Dirac*[54] *has pointed out that continuous creation of matter can be related to the wider questions of cosmology.*[55]".

Following the infatuation around the idea of permanent creation of matter,

48 BONDI et GOLD 1948.
49 EDDINGTON 1931b.
50 BONDI et GOLD 1948, p.259.
51 HOYLE 1948.
52 In this model, the scale factor is $f(t)=\left(C_1+C_2e^{\frac{3}{2}C_3ct}\right)^{\frac{2}{3}}$, where C_1 and C_2 are integration constants, C_3 is linked to the rate of creation.
53 DUBOIS et FÜZFA 2019.
54 DIRAC 1937b.
55 HOYLE 1948, p.372.

Max Born invited Jordan to publish in *Nature*[56]. In this paper, Pascual Jordan compared his model to Hoyle's. Both agreed on the idea of stationary cosmology requiring a process of matter creation to counterbalance the universe dynamics, but they achieved it in very different ways. On the one side, Jordan suggested a spontaneous creation of stars in global energy balance. On the other side, Hoyle proposed the creation of helium saving the energy conservation law in the border of the observable universe. This is why Jordan wrote down :

> "Several decisive ideas of Hoyle's are in full harmony with my own theory [...]. But there are also considerable differences between Hoyle's theory and my own."
> [a]
>
> [a]Ibid., p.640.

Conclusion

Currently, Jordan's name is associated with Jordan's frame and Brans-Dicke's theory[57]. Yet, his cosmological model tends to be forgotten, while it would deserve a brighter place in the relevant literature.

This paper put into light that Jordan was part of the continuity of Eddington's and Dirac's works. Jordan suggested his own cosmological model with the influence of Large Numbers hypothesis and previous works on variation of the constants, such as Sambursky's. Per se, Jordan joined the precursors of all the modified gravity models working on varying constants. His approach could be linked with Wetterich's work[58]. From another point of view, with the spontaneous creation of stellar objects, and more precisely of compact objects, Jordan could be seen as a forerunner of primordial black holes study, later initiated by S. Hawking, B. Carr and others, and nowadays still studied[59].

We hope that this article will put Jordan at the position that is rightly his in the historical development of cosmology, and perhaps arouse an interest for his vast series of publications on his model.

B.3 1937 Année de l'hypothèse des grands nombres

Résumé. En 1937, Dirac propose son hypothèse des grands nombres. à partir de l'étude qu'il fait des constantes de la physique, il bâtit un modèle cosmologique en suivant une approche déductive. Ce faisant, il rejoint une tendance

[56]JORDAN 1949.
[57]BRANS et DICKE 1961.
[58]WETTERICH 2014.
[59]CLESSE et GARCIA-BELLIDO 2017.

initiée par Eddington et suivie par d'autres. Cette nouvelle méthode interpelle Dingle, qui prend position en faveur de l'induction, en opposition à la déduction. Suite à diverses publications, un débat cosmologique et épistémologique prend place dans les pages de la revue Nature. Le présent article propose une revue commentée de cette année particulière, via l'analyse chronologique de diverses contributions. On découvre alors les balbutiements cosmologiques de l'hypothèse des grands nombres ; mais on met aussi en lumière l'importante controverse épistémologique qui s'en suivit.

Abstract. Dirac put forward his Large Numbers hypothesis (LNh) in 1937. Based on his study of physical constants, he built a cosmological model by following a deductive approach. In adhering to this method, he thus joined a trend that had been set in motion by Eddington. This new method countered that of Dingle, who had opted in favour of the opposing camp, namely induction. Numerous publications on this subject sparked a cosmological and epistemological debate within the journal Nature. By analysing various contributions in chronological order, the present article offers a commentary on this noteworthy year. The hesitant cosmological beginnings of the LNh are thereby brought to light, as is the major epistemological controversy that ensued.

Mots Clés : Cosmologie - Epistémologie - Grands nombres - Histoire- Modèles hétérodoxes

B.3.1 Introduction

Le début du XX^e siècle a été synonyme de révolutions dans le champ de la physique. La mécanique classique a été supplantée par la mécanique quantique, d'une part, et par la théorie de la relativité, d'autre part. Cette dernière présente l'avantage de résoudre quelques problèmes de la gravitation newtonienne, tels que l'avance du périhélie de Mercure. De plus, la relativité générale a permis d'élargir l'astrophysique à la cosmologie. Ceci est notamment devenu possible lorsque l'on a découvert que les nébuleuses spirales sont beaucoup plus grandes et plus éloignées que ce qui était attendu ; elles sont des galaxies à part entière, au même titre que la Voie Lactée[60].

Quelques modèles cosmologiques ont alors vu le jour, tels que, sans être exhaustif, l'univers statique d'Albert Einstein[61], l'univers vide de Willem de

[60] Le lecteur intéressé peut consulter les commentaires du grand débat ayant opposé Shapley et Curtis sur la question de la nature extragalactique des nébuleusesShapley et Curtis 1921.

[61] Einstein 1917.

Sitter[62] ou l'univers en expansion de Georges Lemaître[63]. Ce dernier suggère un univers dynamique. Après l'agrandissement du cosmos suite à la découverte de l'existence d'une multitude d'autres galaxies, un second bouleversement s'est produit. Non seulement les nébuleuses sont des galaxies, mais en plus, elles semblent pourvues d'une dynamique[64]. Dans un article de 1929, Edwin Hubble établit une loi reliant la vitesse d'éloignement des nébuleuses extragalactiques à leur distance[65], apportant une confirmation expérimentale au modèle de Lemaître. Si l'univers s'étend avec une vitesse connue, appelée constante de Hubble, il a dû être plus petit par le passé. Cette idée a été explorée par Lemaître dans son modèle d'atome primitif, aujourd'hui devenu la théorie du Big Bang[66].

Cependant, la théorie de la relativité ne convainc pas tout le monde comme en atteste le modèle cosmologique de Edward Milne[67]. L'idée principale en est de travailler dans deux référentiels différents, et donc, avec deux coordonnées temporelles distinctes. Ce modèle repose sur ce qui est maintenant appelé la kinematics relativity.

C'est dans ce contexte scientifique que Paul Dirac envoie une lettre, devenue célèbre, aux éditeurs de Nature[68]. L'objectif de Dirac est de mettre en avant certaines coïncidences numériques entre les constantes de la physique, comme Arthur Eddington l'a déjà fait par ailleurs[69]. De nos jours, peu de personnes sont familières avec le modèle cosmologique construit par Dirac à la suite de cette lettre[70] ; et bien moins nombreuses encore sont celles qui ont connaissance du débat, exposé ici, qui a pris place dans la revue Nature entre ces deux publications.

Ce travail a pour but de présenter et d'analyser toute la controverse en traversant chronologiquement les publications impliquées. Le débat va être replacé dans son contexte scientifique à partir de la lettre de Dirac datée de février 1937 et exposée en section 2 et de celle, moins connue, de Subrahmanyan Chandrasekhar[71] présentée en section 3. L'intervention de Herbert Dingle qui attaque ce qui, selon lui, s'apparente à une nouvelle et mauvaise façon de faire de la

[62] Sitter 1917b.
[63] Lemaître 1927.
[64] Slipher 1913.
[65] Hubble 1929.
[66] Lemaître 1931c.
[67] Milne 1934.
[68] Dirac 1937b.
[69] Eddington 1929.
[70] Dirac 1938.
[71] Chandrasekhar 1937.

science est détaillée en section 4[72]. La publication de Dingle déchaîne alors les passions et force la revue Nature à dédier un supplément au débat émergent. Cette controverse est exposée, avec force détails, en section 5. L'analyse des diverses interventions se fera à partir de la littérature secondaire, en particulier les ouvrages de Helge Kragh et les travaux de George Gale, en collaboration avec Niall Shanks et John Urani. Si ces références sont très intéressantes, il n'en reste pas moins que leurs propos ne sont jamais entièrement centrés sur la controverse de 1937, contrairement au présent travail qui lui ait dédié. Avant de conclure sur l'écho qui pourrait être donné de nos jours au débat épistémologique, l'auteur présentera quelques répercussions ultérieures à 1937 de l'idée initiale de Dirac dans la section 6.

B.3.2 Février *The Cosmological Constants* de Dirac

Pendant la deuxième décennie du XX^e siècle, Arnold Sommerfeld[73] construit, à partir des constantes fondamentales de la physique, la constante de structure fine[74] , nombre pur noté α.

Arthur Eddington a étudié la valeur de cette constante, et pose son inverse comme étant égal à 137[75,76]. En faisant cela, Eddington devient l'instigateur de plusieurs études des constantes. Selon lui, le travail sur les constantes sans dimension permet de toucher du doigt les principes fondamentaux de la science, puisqu'elles sont indépendantes du choix subjectif d'un système d'unités.

Dans ce contexte, le 5 février 1937, Paul Dirac envoie une lettre aux éditeurs de Nature. Ce texte est publié quinze jours plus tard sous le titre *The Cosmological constants*[77]. Dirac se concentre sur de grands nombres tels que le rapport entre les forces électrique et gravitationnelle entre un électron et un proton. Ce rapport a une valeur de 10^{39}, dont le carré correspond au rapport des masses de l'univers et du proton, autour de 10^{78}. De plus, l'âge de l'univers, alors estimé à près de 2 milliards d'années, exprimé en unité atomique de temps[78],vaut lui aussi 10^{39}. Ceci ne peut pas être une coïncidence et amène Di-

[72] Dingle 1937b.

[73] Sommerfeld 1916.

[74] L'ancienne définition de la constante de structure fine, à partir de la vitesse de la lumière, de la constante de Planck et de la charge de l'électron, est correcte dans le système d'unités CGS ; de nos jours, dans le système d'unités international, sa définition fait aussi intervenir la permittivité du vide.

[75] Eddington 1929.

[76] Eddington 1930a.

[77] Dirac 1937b.

[78] Dirac nomme « époque » le nombre pur construit comme le rapport entre l'âge de l'univers et l'unité de temps atomique. Il travaille alors avec un nombre pur qui porte en lui

rac à écrire : « Cela suggère que les grands nombres susmentionnés ne doivent pas être considérés comme des constantes mais comme de simples fonctions de notre époque actuelle, exprimée en unités atomiques[79] »[80]. Ce principe a pour conséquences directes que, d'une part, le nombre de protons et de neutrons doit croître comme le carré de l'époque ; et que, d'autre part, la constante de la gravitation G doit être inversement proportionnelle à l'époque.

L'argument selon lequel il ne peut y avoir de coïncidence est lié au principe de Copernic[81]. L'humanité ne se trouve ni à un endroit spécifique de l'espace, ni à un moment particulier du temps. Cette relation entre les ordres de grandeur de ces rapports doit donc être conservée dans le temps et non pas être particulière à l'époque spécifique à laquelle nous vivons.

Travailler avec des constantes de la physiques variables peut être vu comme équivalent à la cosmologie d'Edward Milne[82]. L'idée de Milne était de travailler avec deux systèmes d'unités, surtout pour les coordonnées temporelles. Dirac utilise beaucoup cette idée, jusque dans les années 1970. C'est une manière de conserver les lois de la mécanique dans l'un des systèmes d'unités et de permettre la variation des constantes de la physique dans le second.

Dans la revue Nature, après les lettres à l'éditeur, il y a une section *Points from foregoing letters*, où sont brièvement résumées les lettres précédentes. Il s'agit là d'un moyen d'encourager le dialogue. Il est donc possible de trouver une présentation de la lettre de Dirac[83]. C'est une présentation succincte d'un article qui n'est déjà pas bien long. Mais, néanmoins, tous les éléments importants y sont repris : les coïncidences, leurs conséquences qui sont la variation de la constante gravifique G et de la masse de l'univers, ainsi que le lien aux travaux de Milne. Hélas, en lisant seulement ce résumé, on peut ne pas saisir la motivation générale de Dirac, qui est plus scientifique que ce qui pourrait être perçu de prime abord.

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la variation de l'âge de l'univers.

[79] La traduction de toutes les citations a été faite par l'auteur

[80] DIRAC 1937b.

[81] Le principe Copernicien, selon lequel il n'y a pas de point de vue privilégié dans l'univers, peut être relié aux travaux de Nicolas de Cues et de Giordano Bruno.

[82] MILNE 1937a.

[83] NATURE 1937a.

B.3.3 Mai *The Cosmological Constants* de Chandrasekhar

En mai 1937, Subrahmanyan Chandrasekhar publie lui aussi, dans la revue Nature, un article intitulé *The Cosmological constants*[84]. Encouragé par le travail de Dirac, il souhaite partager des coïncidences qu'il a remarquées quelques années auparavant.

à partir des constantes naturelles, plusieurs relations ayant une dimension de masse peuvent être construites. Chacune de ces relations peut caractériser une échelle astrophysique particulière : l'étoile, la galaxie ou l'univers tout entier. En appliquant le principe de Dirac, et donc en considérant la variation de G, ces relations s'avèrent être, elles aussi, dépendantes de l'époque. Chandrasekhar arrive donc à particulariser la variation des masses des étoiles, des galaxies et de l'univers selon leurs différentes échelles. De la matière est créée, mais les taux de création diffèrent selon le milieu considéré.

Le comité éditorial de Nature a écrit quelques lignes à propos de cette lettre[85]. La différence fondamentale entre l'idée de création de matière chez Dirac et Chandrasekhar est que chez le premier, la matière est créée en suivant une certaine relation avec l'âge de l'univers, alors que pour le second, il y a différentes échelles d'objets astronomiques et donc différents taux de création de matière, tous fonctions de l'âge de l'univers, mais suivant différentes lois de puissance. De plus, le raisonnement de Chandrasekhar ne dépend pas de coïncidences telles que la redondance de la valeur 10^{39}. Comme les relations construites semblent être vérifiées et qu'elles dépendent de G, si G varie, les relations établies se doivent de varier à leur tour.

Ainsi, Chandrasekhar et Dirac envisagent la création de matière comme un processus physique possible et cohérent avec leur modèle cosmologique respectif. De nos jours, la création continue de matière n'est considérée que comme l'apanage de la Steady State Theory développée par Bondi, Gold et Hoyle à partir de 1948 (voir infra, section 6). L'histoire a eu tendance à oublier les autres modèles stationnaires et les précurseurs des cosmologies requérant de la création de matière.

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[84] CHANDRASEKHAR 1937.
[85] NATURE 1937b.

B.3.4 Mai *Modern Aristotelianism* de Dingle

Une semaine après la publication de Chandrasekhar, Herbert Dingle (1890-1978), physicien et philosophe des sciences, fondateur de la prestigieuse *British Society for the History of Science*, est l'auteur, dans Nature, d'un article concernant ce qu'il appelle l'aristotélisme moderne. Dingle distingue deux approches épistémologiques de la science : il oppose les aristotéliciens aux galiléens.

Originellement, l'aristotélisme était l'idée que la nature est l'expression de principes généraux connus par l'esprit humain sans le biais de la perception sensible. Les aristotéliciensagissent comme si l'esprit humain avait accès à la connaissance des principes régulateurs de la nature. Dans cette vision, la raison peut percevoir le cours de l'expérience sans avoir recours à l'expérience en tant que telle.

Dans l'approche galiléenne, la nature est indépendante. L'esprit humain peut uniquement observer et tenter de décrire ce qu'il perçoit. La raison peut, tout au plus, essayer de corréler les observations dans un système logique.

En opposant ces deux approches, Dingle interroge ce qu'est la science. La question n'est plus de savoir comment bien faire les choses, mais, plus important, quelles choses doivent être faites. Doit-on déduire, à partir de principes généraux, des conclusions particulières ou doit-on induire, à partir des observations, des principes généraux ?

Selon Dingle, Galilée aurait généralement approuvé la science moderne jusqu'aux années 1930, moment où Dingle semble assister au renouveau de l'aristotélisme. Ce n'est plus l'aristotélisme originel, mais une forme évoluée semblable à une idolâtrie où l'Univers prend la place d'un dieu. Ce type de science transcende les observations et ne peut pas être obtenu par induction à partir des seules expériences. Dingle est donc surpris de l'acceptation générale de cette mouvance, ou tout du moins par l'absence de protestation.

Herbert Dingle illustre son propos à l'aide de trois exemples célèbres. Pour le premier, Dingle s'intéresse à Arthur Eddington qu'il considère comme un aristotélicien, surtout à cause de son interprétation de la constante cosmologique comme une constante de la nature. Cependant, puisque Dingle porte une grande estime à Eddington et ne peut imaginer que celuici soit victime d'une pareille chimère, il pense qu'en pratique, Eddington réfute son propre credo.

Edward Milne est le deuxième à être pris à parti. Les critiques de Dingle portent surtout sur le principe cosmologique, qui permet d'étendre la physique étudiée sur Terre à l'ensemble de l'univers afin de pratiquer la cosmologie. Du point de vue de Dingle, cette hypothèse invente un univers sur lequel travailler, mais qui est distinct de celui que l'on observe.

Enfin, Dingle en arrive à Paul Dirac, victime lui aussi de la grande « universmania ». Ce que Dingle retient contre Dirac c'est que celui-ci souhaite expliquer les grands nombres différemment des petits. Sceptique, Dingle souligne que, face à l'infinité des nombres, il est difficile de tracer la frontière séparant les petits nombres des grands.

L'objectif de l'article de Dingle est de faire resurgir le débat sur les fondements de la science : savoir si elle est issue de l'observation ou si elle est pure invention. étrangement, Dingle semble vouloir imposer une manière de penser et de faire aux scientifiques, reniant ainsi sa propre formation de physicien.

Cette publication a provoqué son lot de réactions. Avant de les analyser, il y a quelques remarques qui doivent être faites. Tout d'abord, l'emploi d'Aristote en tant que modèle de référence pour l'approche déductive est discutable. Comme Eric Temple Bell l'a judicieusement noté[86], la déduction est plus la caractéristique d'une science issue du platonisme pythagoricien. En effet, cette approche philosophique de la science repose sur une conception très intellectuelle selon laquelle la nature peut être comprise seulement par l'esprit humain. L'homme de sciences qu'a été Aristote était convaincu de l'importance et du rôle primordial des observations et de l'expérimentation. En choisissant Aristote comme figure de proue de la méthode déductive, Dingle commet une erreur historique.

Ensuite, on peut s'interroger sur la réaction que suscite le principe cosmologique utilisé par Milne. Cette idée est en directe continuité avec le principe d'universalité des lois de la physique. La science repose sur l'hypothèse que les expériences et leurs résultats sont indépendants de leurs localisations spatiale et temporelle. Et, étrangement, alors que ce principe est déjà présent dans des travaux antérieurs largement acceptés, par exemple dans l'article d'Einstein[87] ou de Howard Robertson[88], Dingle attaque uniquement l'usage qu'en fait Milne.

Enfin, la lettre écrite par Dirac peut certainement être critiquée ; mais, l'attaquer sur la définition de ce qu'est un grand nombre par rapport à l'infini,

[86] Temple Bell 1946, p.408.
[87] Einstein 1917.
[88] Robertson 1929.

est plutôt immature, et porte à penser que Dingle n'a pas saisi les subtilités de l'argumentaire de Dirac. Que le lecteur ne perde cependant pas de vue le contexte historico-politique très particulier que connaît l'Europe en 1937. La tentative de Dingle de défendre une science britannique n'est certainement pas sans lien avec les deux régimes politiques contemporains qui tentent d'imposer leur point de vue dans tous les domaines, même dans le champ de la science. Dingle est certainement motivé par un intérêt nationaliste, ce qui expliquerait sa mise en exergue de la première charte de la *Royal Society.* Le fait que le débat exposé ci-après n'ait réuni que des savants issus de Grande- Bretagne n'a pas dû entièrement déplaire à Dingle.

B.3.5 Juin Supplément dans *Nature*

En juin 1937, la revue *Nature* a publié un supplément dédié au débat initié par l'article d'Herbert Dingle, lui-même réponse à la lettre de Paul Dirac. Le comité éditorial a décidé de rassembler, en un supplément, les nombreuses réactions reçues.

Un supplément similaire avait déjà été publié en 1931[89]. Il était alors question de l'évolution de l'univers. L'introduction de ce débat avait été signée des initiales H.D. et peut très certainement être attribuée à Herbert Dingle. Ce débat-là avait eu un rayonnement plus large, car il avait vu intervenir, entre autres, Georges Lemaître (Louvain), Willem de Sitter (Leyde) et Robert Millikan (Pasadena).

En 1937, puisque Dingle a nommément critiqué Edward Milne, celui-ci est choisi pour publier sa réponse en premier lieu. Arthur Eddington poursuit le débat en l'orientant vers le lien entre la physique et la philosophie Ensuite, Paul Dirac prend part à la discussion, répondant sommairement aux reproches émis par Dingle. Après ces trois contributions, plusieurs auteurs partagent leurs points de vue. La conclusion du supplément est laissée à Dingle.

On the Origin of Laws of Nature **de Milne**

La contribution d'Edward Arthur Milne (1896-1950), astrophysicien britannique alors professeur à l'université d'Oxford, n'est rien de plus que la synthèse de ses travaux précédents[90]. Milne confirme l'utilisation du principe cosmologique, hypothèse selon laquelle l'univers a partout les mêmes propriétés. Cependant, ceci n'est pas à mettre en lien avec un quelconque corpus ou une loi de

[89] H.D. 1931, et articles suivants.
[90] MILNE 1937b.

la nature, mais se résume à une question d'économie de pensée. Milne a étudié les conséquences de cette hypothèse sans aucun recours aux lois empiriques de la nature.

Quand Milne mentionne que la physique doit se comporter comme la géométrie, il ne s'agit pas là d'une sur-mathématisation de la science. Il ne fait qu'exprimer son rêve de voir la physique devenir un système complet d'axiomes et de théorèmes comme l'est la géométrie euclidienne. De plus, Milne n'a pas renié le rôle des observations. En fait, il leur en reconnaît deux : découvrir empiriquement de nouveaux théorèmes et vérifier l'exactitude des théorèmes déduits des axiomes. La géométrie elle-même a d'abord été empirique en Ancienne égypte avant de se baser sur la déduction en Grèce Antique ; selon Milne, la physique moderne devrait combiner ces deux aspects.

à plusieurs reprises, Helge Kragh a évoqué cette controverse. En particulier, il a souligné la ferme position rationaliste défendue par Milne et son refus de plier face aux attaques de Dingle[91].

Physical Science and Philosophy d'Eddington

Le ton de la réponse de Sir Arthur Eddington (1882-1944), directeur de l'observatoire de Cambridge, est pour le moins intéressant : il dit de l'article de Dingle qu'il est divertissant et avoue son grand plaisir de l'avoir choqué[92].

Plus sérieusement, Eddington se penche sur la question de l'antériorité des principes généraux. S'il n'est pas possible d'avoir une connaissance a priori de l'univers objectif, alors aucun savoir déduit à partir d'une méthode a priori ne peut porter sur l'univers objectif. Eddington parvient à montrer que les lois de la nature n'expriment jamais une connaissance de l'univers objectif. Il n'y a pas d'élément objectif dans les lois générales, en particulier pour les systèmes observés.

Kragh souligne la satisfaction d'Eddington et revient brièvement sur son argumentaire[93]. Comme beaucoup de choses sont déduites d'arguments a priori, il n'y a pas de connaissance de l'univers objectif. George Gale et John Urani ont aussi retenu de cette intervention que les lois de la physique sont subjectives parce qu'elles sont issues d'a priori épistémologiques[94].

[91] Kragh 1999, p.70.
[92] Eddington 1937.
[93] Kragh 1982, p.100.
[94] Gale et Urani 1999, p.358.

Contribution de Dirac

Paul Adrien Maurice Dirac (1902-1984), célèbre physicien et prix Nobel, à son tour, prend part au supplément de Nature[95]. Il peut ainsi répondre aux attaques directes de Dingle. Dirac est d'avis que la science doit être un équilibre entre ce qui est induit à partir des observations et ce qui est déduit d'hypothèses spéculatives. La science se fait par ces deux approches et la lettre de février 1937 impliquait ces deux vues.

En effet, Dirac a basé son travail sur des constantes astronomiques et atomiques fournies par les observations. Il a ensuite construit, à partir de ces constantes, les nombres purs les plus simples. Dirac est interpelé par le caractère peu aléatoire des nombres ainsi construits qui semblent être regroupés. Les valeurs 10^{39} et 10^{78} en tant que telles ne sont pas importantes. Ce qui doit être expliqué c'est la redondance des lois de puissance entre elles. Ce fait a mené Dirac à proposer une hypothèse selon laquelle le regroupement des nombres purs est un phénomène naturel fondamental, conservé au cours du temps. Cette hypothèse a des conséquences telles que les nombres de l'ordre de 10^{39} doivent croître.

Dirac mentionne aussi la publication de Subrahmanyan Chandrasekhar. Avec les coïncidences mises en avant par celui-ci, il est possible d'exprimer les masses stellaires et galactiques moyennes comme étant proportionnelles à 10^{39}. Donc, il devient facile de calculer les différents taux d'accroissement des masses stellaires et galactiques au cours du temps.

Dans sa biographie de Dirac, Kragh évoque le supplément de Nature. Selon lui, la réponse de Dirac est une expression assez claire de sa façon d'éviter les débats : Dirac reconnaît l'importance des deux méthodes, inductive et déductive, en plaidant pour un équilibre entre elles[96]. Cependant, Dirac refuse de prendre part à la discussion philosophique.

Contribution de McCrea

William McCrea (1904-1999), directeur du département de mathématique de l'université Queen's de Belfast, réagit lui aussi à la controverse. Selon lui, le discours de Dingle contre l'aristotélisme est typiquement aristotélicien. Galilée aurait vu que ceux que Dingle accuse d'aristotélisme ne peuvent déduire des propriétés du monde qu'avec un esprit humain qui interprète les expériences

[95] DIRAC 1937a.
[96] KRAGH 1990.

sensibles. Un galiléen se concentrerait sur le lien entre les mondes de la physique et de l'humain. De plus, Dingle utilise la citation de Galilée : « La nature ne se soucie pas de savoir si ses raisons et méthodes de fonctionnement abstruses sont ou non exposées au pouvoir des hommes »[97] ; ce qui constitue un parfait exemple d'idée a priori sur la nature qui ne repose sur aucune preuve observationnelle. Ce qui, alors, voudrait dire que Galilée serait aristotélicien au sens de Dingle.

Dans l'idée développée par McCrea, Dingle questionne le lien entre la physique mathématique et la physique expérimentale, jugeant la première « nouvelle et perverse ». Alors que la physique mathématique est une conséquence mathématique des hypothèses. Une telle physique est jugée sur la simplicité et le nombre de ses hypothèses ainsi que sur l'observation de ses prédictions. Dans ce contexte, le terme d'hypothèse doit être compris dans son acception mathématique, il n'est pas requis qu'elle soit vraie, mais elle doit être cohérente. La physique mathématique progresse en augmentant le nombre de ses hypothèses et en observant ses prédictions. Par ailleurs, les scientifiques doivent être motivés non par l'opportunité de railler l'hypothèse de leurs collègues, mais en testant leur succès.

Pour conclure, McCrea prend la précaution rhétorique de s'assimiler aux fous d'un célèbre proverbe anglais : « Les fous se précipitent là où les anges ont peur de marcher ». Ce qui peut être interprété comme une reconnaissance de son ignorance dans ce débat. Ou alors, cela doit peut-être être compris comme un avertissement pour les insensés qui voudraient prendre part à la discussion.

Gale et Urani, dans leur étude de ce débat, soulignent la qualité de l'argument ad hominem développé par McCrea, renvoyant Dingle du côté de l'aristotélisme[98]

Contribution de Haldane

John Haldane (1892-1964), généticien britannique, prend lui aussi le parti de Milne. Il parle au nom des biologistes et des géologues pour qui la kinematics relativity de Milne pourrait avoir d'importantes répercussions. Il admet que si Milne travaillait sans recours à l'expérience, Dingle pourrait le qualifier de traître à la science. Mais le principe cosmologique tel que Milne l'utilise n'est pas un principe détaché de l'expérience. En effet, c'est un moyen d'exprimer que nous ne sommes pas des observateurs privilégiés de l'univers. Et cela dé-

[97] Dingle 1937b.
[98] Gale et Urani 1999, p.361.

coule, entre autres, du fait que notre Soleil n'est pas une étoile particulière.

à propos de la citation d'Eddington au sujet d'un système de pensée qui devrait être capable d'obtenir toute la connaissance du monde physique, Haldane révèle qu'un tel système ne pourrait pas être construit sans recours à l'expérience sensible.

L'article de Dingle du mois de mai n'empêchera pas les géologues et les biologistes de travailler avec les deux coordonnées temporelles introduites par Milne. La conclusion d'Haldane est parfaitement claire : « Si les résultats servent à éclairer l'histoire géologique et organique de l'évolution, on devrait être trop occupés pour trouver du temps pour le (Milne) blâmer pour le récit indûment trop idéaliste de leurs origines »[99].

Gale et Urani interprètent l'enthousiasme d'Haldane pour l'argument de Milne à la lumière des écarts entre l'estimation de l'âge de la Terre pour la géologie et l'âge du monde pour la physique. La double échelle temporelle proposée par Milne pourrait s'avérer efficace dans ce contexte[100].

Contribution de Jeffreys

Alors que son livre *Scientific Inference* en est à sa deuxième édition, Sir Harold Jeffreys (1891-1989), statisticien et géophysicien attaché au St John's College de Cambridge, se joint au débat. Jeffreys est complètement d'accord avec le point de vue de Dingle. Avec son bagage de statisticien, Jeffreys a proposé un ensemble de postulats qui vont permettre à tous les types d'observations d'être assimilés dans une théorie, sans devoir supposer que différents principes d'apprentissage soient requis dans des sujets différents.

Ce système de postulats est satisfaisant parce que : 1) Il ne traite aucune hypothèse comme sûre a priori ; 2) il fournit des méthodes pour choisir entre des hypothèses par le biais des observations ; 3) il estime les paramètres impliqués dans les hypothèses, cohérents avec les observations ; 4) il admet que toutes les décisions peuvent être mauvaises, mais sont prises avec un certain degré de confiance ; 5) il est prêt à corriger ces mauvaises décisions, puisque la science progresse par des approximations successives.

Dans l'approche de Jeffreys, le problème actuel en science vient de la croyance en une vertu spécifique des mathématiques. Les physiciens oublient que les mathématiques ne sont qu'un outil. Les mathématiques se contentent de connecter

[99] HALDANE 1937, p.1004.
[100] GALE et URANI 1999, p.360.

postulats et observations. La déduction est utile pour investiguer les conséquences d'une loi admise, tant qu'elle est une approximation de l'induction.

Dans leur analyse du débat, George Gale et Niall Shanks remarquent que Jeffreys soutient Dingle pour des raisons inductivistes, anti-mathématiques[101]. On peut voir que l'argumentaire déployé par Jeffreys porte davantage sur le rôle des mathématiques que sur le fondement épistémologique de la controverse.

Contribution de Campbell

Norman Campbell (1880-1949), philosophe des sciences, appuie son intervention sur la définition de la science donnée par W.H. George, auteur de *The scientist in action*, « la science est l'activité des scientifiques ». Ainsi, il ne peut pas y avoir d'hérésie en science, seulement de l'orthodoxie. Si certaines spéculations peuvent être perçues comme fantastiques ou métaphysiques, la question n'est pas de savoir si elles sont déloyales vis-à-vis de la tradition scientifique du $XVII^e$ siècle, mais pourquoi ces nouveaux intérêts sont apparus si soudainement.

Selon Campbell, le nouveau développement aurait pu être prédit. En effet, la physique est construite par deux activités complémentaires menées par des profils différents. D'une part, les expérimentateurs qui ne développent pas de théorie, d'autre part, les théoriciens qui ne font pas d'expériences. Pendant longtemps, les physiciens étaient, tour à tour, l'un et l'autre, mais récemment, ils se sont spécialisés.

Les expérimentateurs travaillent avec l'induction, ils trouvent des lois démontrables qui expliquent les expériences. Ils construisent la connaissance par accrétion. Alors que les théoriciens construisent des théories pour expliquer des lois. Hélas l'interprétation du mot « expliquer » est variable. Pour l'instant, le procédé théorique est subdivisé en trois étapes. Le théoricien doit formuler des hypothèses, en déduire les conséquences et traduire ses conclusions en propositions. La particularité des explications scientifiques est que, non seulement elles expliquent les anciennes lois, mais elles en prédisent de nouvelles.

Jusqu'au début du XX^e siècle, la physique fonctionnait par analogies et avec des théories mécaniques. Campbell fait remarquer que la méthodologie a changé et que les hypothèses sont désormais exprimées dans un langage plus mathématique. En cela, Dirac est en directe continuité avec le développement

[101] Gale et Shanks 1996.

historique des sciences et les critiques de Dingle n'ont pas lieu d'être.

Gale et Urani commentent la réponse à la fois logique et historique de Campbell[102]. Son argumentation indique avec succès que l'émergence de la déduction en science est compréhensible et ne constitue pas une rupture.

Contribution de Filon

Sans être entièrement d'accord avec la position de Dingle, Louis Filon, professeur au University College de Londres, accueille favorablement sa protestation contre la tendance à travailler, en physique, à partir de théories mathématiques abstraites. Les faits et les observations mènent à des lois particulières, pas à pas, en utilisant l'induction. Ceux qui tentent de résoudre le problème complet de la nature grâce à des déductions mathématiques n'expliquent pas la nature, ils explorent juste l'esprit humain. Selon Filon, il est temps de revenir aux méthodes plus sûres du XIX^e siècle.

Comme le font remarquer Gale et Shanks, tous les mathématiciens ne défendent pas la méthode de Milne, Eddington et Dirac[103]. Filon soutient Dingle contre ceux qui pensent possible de résoudre le problème de la nature à l'aide de l'unique intuition mathématique.

Contribution de Peddie

Le physicien écossais William Peddie (1861-1946) intervient dans le débat de manière brève et absconse. Il voit dans la contribution de Dingle l'idée qu'il pourrait être temps de changer l'angle d'attaque (métaphysique) des problèmes physiques. Au lieu de blâmer les lois de la pensée pour la structure de l'univers, on peut en vouloir à l'univers pour les lois de la pensée. On peut alors s'échapper de l'aristotélisme et retourner aux côtés de Galilée et de Newton.

Comme en rendent compte Gale et Urani, l'objectif de Peddie est de remettre la physique sur ses fondements empiriques[104].

Contribution de Sampson

L'astronome Ralph Allan Sampson (1866-1939) intervient aussi dans le débat. Sa position se construit sur un simple constat : nous, humains, sommes limités. Nos sens sont limités et ils sont notre unique porte ouverte sur le monde. Notre

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[102]Gale et Urani 1999, p.360.
[103]Gale et Shanks 1996, p.290.
[104]Gale et Urani 1999, p.364.

temps est lui aussi limité. Dès lors, Sampson n'est pas aristotélicien et personne ne l'est, car il est impossible de l'être.

Même ceux qui se disent aristotéliciens ne le sont pas : puisque les humains sont limités, il leur est impossible de faire des déclarations absolues. De plus, si les théories sont écrites dans le langage mathématique, elles ne peuvent pas parler du temps, car les mathématiques ne sont pas outillées pour exprimer le temps. En sciences, on doit se satisfaire de théories qui n'expriment que l'essentiel de ce qu'on souhaite exprimer. Chaque postulat est extrapolé de l'expérience, elle-même partiellement correcte.

Contribution de Darwin

à son tour, Charles Galton Darwin (1887-1962), mathématicien attaché à Cambridge et petit-fils de son célèbre homonyme, a rejoint la discussion. D'après lui, ce qui est important dans l'article de Dingle du mois de mai, ce n'est pas la critique envers l'aristotélisme, mais la résurgence et la persistance du questionnement sur l'étrange relation entre métaphysique et science.

D'un côté les philosophes développent la métaphysique qui sous-tend toutes connaissances possibles et donc, en particulier, les savoirs scientifiques. Si les métaphysiciens nous disent ce qu'il est permis de penser, peut-être clôtureront-ils la controverse. D'autre part, les scientifiques ont leur propre philosophie, tout en étant rarement formés à philosopher. Ce qui ne les empêche pas de défendre leur position avec enthousiasme et ferveur. Cependant, les positions philosophiques des hommes de sciences sont diverses.

Darwin rappelle que Dingle et Milne passeront bien à la postérité, mais pour leurs travaux scientifiques et non leur position métaphysique. Leur philosophie des sciences pourrait être entièrement dévoilée par un philosophe expert qui pratiquerait une maïeutique socratique. En faisant ainsi, il exposerait les inconsistances et l'impossibilité de leur système.

Revenant à la problématique qui nous occupe, Darwin ne choisit pas de camp. La position de Dingle en faveur de l'induction et contre la déduction est cependant, note-t-il, difficile à tenir. Si Dingle critique la prédiction de Dirac quant à l'âge du monde à partir de coïncidences numériques, quelle serait sa réaction face à l'intuition de Maxwell selon laquelle la relation entre les champs électrique et magnétique se doit d'être la vitesse de la lumière. Quant aux antagonistes de Dingle, ceux qui défendent que la nature et ses lois sont incluses dans notre esprit, ils n'apportent pas de postulat très important. Ce n'est pas parce qu'on a toutes les règles des échecs à l'esprit que l'on gagne constamment.

Helge Kragh fait part du choix de Darwin de ne pas prendre parti[105]. S'il n'est pas un partisan de l'approche de Dirac, il ne fait néanmoins aucune attaque à l'encontre de la position de Dingle.

Contribution de Whitrow

Le jeune Gerald Whitrow (1912-2000), étudiant en doctorat à Oxford, est très certainement intervenu dans le débat pour défendre son mentor Milne, mais il développe un argumentaire fort intéressant. En lisant Dingle, Whitrow y voit une attaque de la méthode d'investigation mathématique en relativité générale et en cosmologie, ainsi qu'un refus d'admettre que c'est un sujet intéressant, bien que fondé à la fois sur l'expérimentation et sur le raisonnement.

Dingle semble avoir un point de vue erroné, une interprétation mystique de ce qu'est réellement l'histoire de la méthode scientifique. Whitrow imagine l'empiriste Dingle à l'époque de Copernic. Le modèle copernicien ne lui semblerait alors qu'une pseudo-science, une « cosmo-mythologie ». Dingle aurait certainement préféré le modèle de Ptolémée basé sur l'induction. Dingle semble oublier que la force de Kepler résidait dans sa croyance en l'harmonie mathématique de la nature. Galilée lui-même usait des mathématiques comme d'un outil d'investigation scientifique et n'évoquait les expériences que pour répondre à ses détracteurs. D'ailleurs, la citation de Galilée utilisée par Dingle n'a été écrite que contre la téléologie scolastique. Pour Galilée, la nature est compréhensible pour l'homme via son esprit.

Depuis Copernic, ce qu'on appelle science moderne repose sur trois prémisses méthodologiques. Tout d'abord, il est supposé que la nature soit uniforme et simple. Ensuite, les scientifiques croient en la possible description de la nature à l'aide des mathématiques. Enfin, on refuse l'anthropocentrisme. Milne, dont Dingle attaque le principe cosmologique, s'inscrit dans la lignée directe de la science de la Renaissance et de la science moderne.

Gale et Urani font remarquer l'excellent argument méthodologique mis en place par Whitrow[106]. En effet, l'interprétation idéalisée, mystique, de l'histoire des sciences défendue par Dingle peut souffrir quelques reproches. Whitrow démontre aussi comment, selon lui, Dingle n'a pas compris Galilée.

[105] KRAGH 1982, p.101.
[106] GALE et URANI 1999, p.362.

Contribution de McEntegart

William McEntegart (1891-1979) *s.j.*, enseignant, entre autres, la cosmologie thomiste au Heythrop College dans l'Oxfordshire, souligne une incompréhension philosophique. Il se demande pourquoi Herbert Dingle a choisi Aristote pour représenter les physiciens de la déduction. Ils auraient pu être appelés kantiens, hégéliens ou fichtéens, mais pas aristotéliciens. En effet, dans cette problématique, Aristote aurait soutenu Dingle. Le besoin d'un fondement philosophique, métaphysique, épistémologique, de toute rationalisation des observations doit, cependant, être reconnu.

D'après Gale et Urani, McEntegart ne prend pas position dans le débat et ne fait que corriger l'usage incorrect du terme aristotélicien[107]. Cependant, conclure sa contribution en disant qu'Aristote aurait soutenu la position de Dingle est plutôt ironique.

Contribution de Stafford Hatfield

Henry Stafford Hatfield (1880-1966), auteur de *The Inventor and his world*, apporte un argument peu conventionnel, Dingle a négligé un important facteur de progrès en science : l'attrait pour les esprits géniaux. Les génies préfèrent se concentrer sur des domaines qui permettent une grande latitude pour l'imagination et la créativité. La plupart des plus grands esprits combinent l'approche de rigueur factuelle et de raisonnement avec des spéculations pleines d'imagination. En se contentant d'être galiléen, comme Dingle le définit, on recrutera bien moins de génies.

Gale et Urani remarquent le point de vue très pragmatique développé par Hatfield[108]. Même si sa remarque est valide, elle n'est pas de grande importance dans le débat opposant l'induction à la déduction.

Contribution de Dawes Hicks

Selon Georges Dawes Hicks (1862-1941), professeur émérite de philosophie, le point fort de l'argumentation de Dingle, ce sont ses arguments justifiant la protestation qu'il oppose à la façon dont certains décrivent le monde physique. Mais Dingle fait porter le chapeau aux mauvaises choses, il tord la signification des mots tels que galiléen et aristotélicien.

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[107] Gale et Urani 1999, p.358.
[108] Ibid., p.359.

Aristote n'est pas un parangon du raisonnement à partir de principes généraux. Que du contraire, Aristote a travaillé in abstracto à partir des expériences, au travers de ce que le monde pouvait fournir en perceptions sensibles. Aristote ne remet pas en question la validité des données sensibles. En cristallisant une prétendue opposition entre les approches scientifiques de Galilée et d'Aristote, Dingle échoue à décrire correctement ce qu'il reproche à la physique moderne.

Deductive and inductive methods in science : a reply de Dingle

Afin de clore le débat prenant place dans les pages de la revue Nature, Herbert Dingle a la possibilité de répondre à toutes les réactions détaillées ci-devant (Dingle, 1937b). Premièrement, il tient à clarifier l'idée que sa publication ne se voulait pas une attaque et il affirme son plus grand respect pour Edward Milne. Ensuite, il rappelle qu'à la première occurrence du mot aristotélicien dans son texte, celui-ci avait été placé entre guillemets. L'objectif étant de caractériser ceux que Newton et Galilée appelaient des aristotéliciens et non pas les véritables disciples d'Aristote.

De plus, Dingle souhaite faire une distinction entre ce que William McCrea appelle hypothèse mathématique, qui peut être assimilée à un axiome, et ce qu'était une hypothèse mathématique du temps de Newton, quand les mathématiques étaient moins développées. Il est important de préciser quel sens d'hypothèse mathématique s'applique au principe cosmologique. Dingle définit la science comme la découverte des vérités de la nature. Toute la question est donc « Peut-on découvrir la vérité sur la nature rationnellement, c'est-à-dire sans aucun recours à l'expérience ? ». Dans un cadre ainsi posé, le conflit entre l'induction et la déduction est, selon Dingle, gagné par l'induction.

à propos de la réaction d'Arthur Eddington, Dingle se réjouit de leur accord sur l'impossibilité d'un quelconque savoir a priori à propos de l'univers objectif. Mais, Dingle n'est pas certain qu'Eddington applique cette idée dans son travail, et Dingle craint qu'il n'y ait une incompréhension non dans le fait d'Eddington, mais pour ses lecteurs assidus.

Dans l'approche défendue par Dingle, il semble que Milne ne s'intéresse pas à la science, il souhaite juste construire une théorie. En réponse à Gerald Whitrow, Dingle souligne la confusion existante entre inexactitude, conflit avec les faits, et irrationalité, conflit avec la raison. Il est également à noter que Dingle ne fait aucune mention des quatre auteurs à se ranger de son côté (Jeffreys, Filon, Peddie et Hicks), un tiers des intervenants extérieurs.

Pour ce qui est de l'argumentaire de Charles G. Darwin, que Dingle résume comme « peu importe ce que l'on pense de la science tant qu'on la fait avancer », Dingle propose une rapide analogie : peu importe ce que l'on brûle pourvu que le feu soit bon. Ce dernier point montre, s'il le fallait encore, que le supplément édité par Nature n'est en fait qu'un dialogue de sourds.

B.3.6 Variation des constantes et création de matière après 1937

En décembre 1937, Paul Dirac soumet pour publication un développement cosmologique de son hypothèse des grands nombres sans aucune référence au débat ici détaillé[109]. Cet article propose un modèle d'univers constitué d'un feuilletage d'hypersurfaces planes et d'un espace infini. Cette théorie requiert un procédé de création de matière. Un tel processus prend difficilement place dans la théorie physique. Puisque, en cette fin des années 1930, il y a d'autres modèles cosmologiques cohérents, il ne vaut pas la peine, selon Dirac, d'étudier plus en détail ce modèle particulier. Cependant, pendant les années 1970, Dirac reviendra aux conséquences cosmologiques de son hypothèse des grands nombres dans plusieurs travaux[110,111].

Dirac a inspiré d'autres modèles cosmologiques faisant intervenir la variation de G et un processus de création de matière. Pascual Jordan a construit, dès 1937, une cosmologie basée sur la motivation d'Eddington d'expliquer la valeur des constantes et l'idée de Dirac de la variation de G. La version la plus aboutie de ce modèle est publiée en 1939[112,113]. Jordan propose un univers dans lequel la matière est créée sous la forme d'apparition spontanée d'étoile. Ce qu'il motive par l'observation d'étoiles jeunes et vieilles. De plus, il étudie les possibles conséquences géophysiques de la variation de la constante de gravitation.

Un modèle plus célèbre de cosmologie faisant appel à la création de matière est la Steady State Theory présentée parallèlement par Bondi et Gold[114] et Hoyle[115]. Fred Hoyle apporte une plus grande mathématisation de ce modèle et le soutiendra jusqu'à la fin de sa vie en 2001. Dans cette cosmologie de la

[109] Dirac 1938.
[110] Dirac 1974.
[111] Dirac 1979.
[112] Jordan 1939a.
[113] L'auteur a récemment publié une traduction commentée de cet article Dubois et Füzfa 2020.
[114] Bondi et Gold 1948.
[115] Hoyle 1948.

matière est créée sous la forme d'atome d'hydrogène tout d'abord et puis, au fur et à mesure des avancées de la physique subatomique, sous la forme de particules de plus en plus petites.

Quant à la question de l'étude des constantes, celle-ci reste toujours d'actualité, comme en attestent les ouvrages relativement récents de Jean-Philippe Uzan et Roland Lehoucq[116] d'une part, ou celui de John Barrow[117] d'autre part. Uzan a travaillé notamment à augmenter la précision de la mesure de la valeur de G. Une telle étude pourrait un jour apporter la preuve expérimentale de la variation de cette constante. Une revue des contraintes expérimentales sur les valeurs des constantes et des différentes idées sur leur variation peut être retrouvée dans l'article d'Uzan[118].

B.3.7 Conclusion

Puisque la définition de la science est sujette à discussion et que les approches déductive et inductive présentent toutes deux des avantages et des inconvénients, des partisans et des opposants, ce débat ne sera jamais clos[119]. Cependant, la lettre de Dirac a eu le mérite de réactualiser la controverse et de permettre aux scientifiques d'alors d'y réfléchir et de prendre position.

Il semblait important à l'auteur de présenter cette controverse dans sa globalité. En exposant ses antécédents et en explicitant ces interventions, cet article s'inscrit dans la lignée de la littérature secondaire qu'il cite. Cependant, c'est un souci de complétude qui a motivé cette publication. La controverse est méconnue, ses commentaires ont plus de quinze ans et sont perdus dans des ouvrages divers et ayant un sujet plus large.

Cet article a non seulement pour but d'effectuer un travail de revue, mais aussi de donner à penser à ses lecteurs : aussi bien sur le débat de 1937 que sur celui qui pourrait avoir lieu aujourd'hui en cosmologie, ou en d'autres champs scientifiques. En effet, pour ce qui est de la cosmologie, cette science a beau avoir acquis un aspect expérimental qu'elle n'avait pas à l'époque et se reposer sur plus d'observations qu'alors, elle reste toujours le fruit d'une profonde mathématisation. Par ailleurs, la scission entre théoriciens et expérimentateurs va toujours en s'agrandissant. L'espoir que porte cette publication est de les faire s'interroger sur les approches scientifiques déductive et inductive afin qu'ils

[116]UZAN et LEHOUCQ 2005.
[117]BARROW 2005.
[118]UZAN 2011.
[119]KRAGH 2004, p.189.

puissent, peut-être, prendre position.

De plus, les quelques récits de l'histoire de la cosmologie portent le plus souvent sur le développent du paradigme actuel : sur la façon dont l'idée de l'atome primitif est devenue le modèle du *Big Bang* chaud. Cette contribution a l'ambition d'explorer les tortueux chemins que les cosmologistes peuvent emprunter. Les grands esprits, comme Dirac ou Chandrasekhar, n'ont aucun souci à suivre leur intuition même si celle-ci les mène à l'idée de création de matière. Sans aucune donnée expérimentale, il était justifié d'investiguer tous les modèles cosmologiques possibles. Il serait bon de se demander si un tel foisonnement d'idées est encore possible aujourd'hui.

Enfin, l'auteur regrette non seulement la séparation, même si elle est poreuse, entre théoriciens et expérimentateurs, mais aussi le mur qui s'est construit entre les différentes disciplines, comme la philosophie et la physique. Le débat de 1937 est, sans aucun doute, un débat épistémologique, néanmoins la grande majorité des intervenants est issue de ce qu'on appelle couramment les sciences dures. La richesse de ce débat soutient l'idée que de plus nombreux ponts devraient être construits entre les disciplines académiques usuellement séparées.

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