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The Vicissitudes of Modern Cosmology

Organon 22 23, 227-258

1986 1987

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INTRODUCTION

Cosmology is one of the youngest of the sciences: but with undoubtedly the longest history.* Modern cosmology was founded by the observational discovery of red-shifts in the galactic spectra, as well as Einstain's theoretic work of 1917. But the history of a science of the Cosmos goes back to the beginnings of human thought.

Studies in the history of science are rewarding by themselves; recently they have also become a tool in the research work of philosophers of science. At the early stages of modern philosophy of science, one subjected to scrutiny concepts such as those of empirical fact, hypothesis, law of nature. Later on, attention was focused on the scientific theory, its structure and epistemological status. Then the treatment of specific theories in isolation was seen as a vivisection performed on the body of science. In science there are no absolutely isolated subsystems; science is to be considered as a whole. Moreover, science is no static phenomenon, it is a process. Here philosophy meets history.[1]

This essay looks at the evolutionary process of modern cosmology; but the mere history of cosmology will interest us less than the changes that occurred

* I want to express my thanks to Dr. Konrad Rudnicki for precious remarks and comments.

Note added in proof. This review paper was written in the beginning of the seventies. Since then many important advances took place in cosmology. Although the history of cosmology has not changed, now we are looking at it from a new perspective. In spite of this, the bulk of the paper, as published now in English translation, has remained the same, only a few references to a newer scientific literature have been added. Perhaps it is worth mentioning that the studies undertaken in this article have matured to the shape of the book entitled *The Evolution of the Cosmos and Cosmology* (in Polish) which has been published by the PWN (Państwowe Wydawnictwo Naukowe), 1st ed. 1983. 2nd ed. 1985.
June 1983

[1] Cf. for example, T. S. Kuhn, *The Structure of Scientific Revolutions*, Chicago 1970.

in its position as a science, in its structure and in its style. The contemporary period in the evolution of cosmology we consider to be, somewhat arbitrarily, the period going from the rise of General Relativity Theory till the present moment.

There are two known monographs concerning the evolution of cosmological thought between the end of the 19th to the beginning of the 20th century.[2] Much has changed in cosmology since the time of their publication. This of course does not negate the historical value of those studies. But history of science differs from all other histories in the fact that, from the perspective of new achievements, the past is seen not only more critically, but quite often simply more clearly. The survey of contemporary cosmological ideas presented in this article has no claim to completeness. It was made from the viewpoint of the author's personal interests. Particularly severe was the selection made among the most recent events happening in the cosmological arena. A personal point of view is not too high a price to pay for the possibility to observe a dynamically developing science.

A case study of contemporary cosmology may be equally instructive for the historian as for the physicist. This is so because this subject-matter is an example of the birth of a new empirical science. The known relativist Peter G. Bergmann[3] confesses:

> Throughout much of my life as a scientist, I retained the feeling that cosmology as a science was not quite "nice" and that it lacked an empirical foundation more than almost any other discipline among the so-called exact sciences. Whether or not my feelings were ever justified, the situation in cosmology has changed so rapidly, and so profoundly, within the last few years that my original reservations have lost any basis in fact that they might have had.

THE FIRST PROBLEMS IN CONTEMPORARY COSMOLOGY

Because of the uniqueness of the object of cosmological studies (only one specimen of the Universe is given us) and because of the scope of extrapolation cosmology obviously needs, it seemed for a long time that considerations about the Universe will remain in the realm of speculation, and that cosmology itself will never rank among the exact sciences.[4] However, in the 19th century there appeared certain problems that had a definite cosmological ring to them and that for the first time engaged in this field both a scientific theory and empirical investigations. A parallel development of the theory and the empirical foundation is decisive for the scientific character of a given field. These were then the first symptoms of cosmology maturing as a science.

The photometric and the gravitational paradoxes constituted an attempt—

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[2] J. Merleau-Ponty, *Cosmologie du XX^e siècle*, Gallimard 1965; J. D. North, *The Measure of the Universe*, Oxford 1965.

[3] P. G. Bergmann, "Cosmology as a Science", *Foundations of Physics*, **1**, 1970, 17—18.

[4] For a survey of earlier cosmological speculations see for instance, A. Koyré, *Du monde clos à l'univers infini*, Paris 1962; S. Groueff, J.-P. Cartier, *L'homme et cosmos*, Paris 1975.

unsuccessful for the moment—to confront some recognized scientific theories with some elementary observational data concerning the Universe. These attempts created a climate in which future cosmological theories could be born. However, the controversy about the "insular" repartition of matter in the Universe was essentially an observational problem. From it arose extragalactic astronomy—the empirical basis of contemporary cosmology.

From Newton's time on, scientists became convinced of the spatial and temporal infinity of the Universe. Space was imagined as an infinite vessel, containing stars with—on the average—an evenly dense distribution; time was considered something "flowing" from past to future, similar to an oriented straight line without beginning or end. These views, though suggested by classical mechanics, resulted mainly from the philosophical doctrine of Newton on absolute space and time. Moreover, since the Copernican revolution in astronomy, the view about the non-distinguished position of the Earth in the Universe was gaining more and more ground. If all locations in the Universe are equally acceptable, then there are no boundary locations: the Universe should be infinite.

On the basis of such a world picture, it was "reasonable" to admit that the mean number of stars in a unit volume is constant—provided the mean is taken over sufficiently large regions—and that the mean luminosity of a star is constant—provided the mean is taken over sufficient lengths of time. This last assumption did not agree with certain cosmological generalizations of the second law of thermodynamics, it was however tacitly admitted in many astronomical considerations. In addition, till the end of the 19th century, there was no reason to suppose that space could be non-Euclidean; that in the realm of stars there may occur systematic movements on a large scale; that in other regions of the Universe other laws than those of classical physics may be valid; and so we have a complete list of assumptions universally admitted in cosmological speculations of that time (with few exceptions, such as Clifford and Riemann).

From just these assumptions, two astronomers (probably independently of one another), P. L. de Cheseaux[5] already in 1744 and H. W. M. Olbers[6] in 1823, derived a conclusion that was in so obvious discrepancy with the most elementary observations that it earned the name of paradox. A simple reasoning shows that the intensity of light coming from stars inside a sphere with radius r and seen from the centre of that sphere, is independent of r. In an infinite Universe, we may surround a sphere with radius r with an arbitrary number of layers of thickness dr; the contribution to light intensity from stars inside any such layer is $U dr$, where U is the product of the average number of

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[5] P. L. Cheseaux, *Traité de la comète qui a paru en décembre 1773*, Paris 1744 (in the "Appendix").

[6] M. Olbers, *Astronomisches Jahrbuch nebst einer der neusten in die astronomische Wissenschaften einschlagenden Abhandlungen, Beobachtungen und Nachrichten*, Berlin 1823.

stars in a unit volume by the average brightness of the star; therefore the luminosity density in the center of the sphere diverges. If we take into account the effect of light being shielded by stars on its way, we obtain as result that the intensity of luminosity in the center of the sphere is equal to the average surface density of luminosity of the shielding stars. An observer in the centre of the sphere should see the heaven shining with an equal glow. Evening observations prove us that this is not so.

Repeating Olbers's way of reasoning, H. von Seeliger[7] noticed that the gravity potential $\varphi = \int (\varrho/r)\,dv$ originating from matter distributed with a constant mean density ϱ in an infinite space ($v \to \infty$) should have no definite value at any point. In order to avoid this paradoxical conclusion, corrections were proposed to Poisson's classical equation, that would allow a static and uniform distribution of matter in an (infinite) Newtonian space. Carl Neumann[8] for instance proposed the following amended form for Poisson's equation:

$$\Delta\varphi = 4\pi\gamma\varrho + \lambda\varphi,$$

where γ is Newton's gravitational constant,
λ a certain new constant,
$\lambda\varphi$ a cosmological term generalizing Poisson's ordinary equation. These *ad hoc* propositions had little chance to gain a permanent foothold in physics.

These two paradoxes, the photometric one and the gravitational one, were to be resolved by the hierarchical model of the Universe, suggested in 1761 by J. Lambert[9] and developed later by C. V. I. Charlier.[10] According to this model, N_1 stars form a galaxy with mass M_1 and radius R_1; N_2 galaxies form a metagalaxy with mass M_2 and radius R_2, and so on indefinitely. The density of a system of i-th order, in the Euclidean space and if (for simplicity's sake) the systems are spherical, is:

$$\varrho_i = \frac{3M_i}{4\pi R_i^3}.$$

When $i \to \infty$, then $\varrho_i \to \infty$; this in principle removes the difficulties of Olbers and Seeliger. Charlier's model, though not inconsistent with observations at the time of its birth, was then only a speculative possibility.

Paradoxes played an important role in the development of the science of the

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[7] H. von Seeliger, *Astronomische Nachrichten*, 1895; *Sitzungsberichte der K. Bayerischen Akademie der Wissenschaften zu München*, 1896 (quoted after: J. D. North, *The measure of the Universe*, Oxford 1965, p. 16).

[8] C. Neumann, *Allgemeine Untersuchungen über das Newtonische Prinzip der Fernwirkungen*, Leipzig 1896.

[9] J. Lambert, *Kosmologische Briefe*, Augsburg 1761.

[10] C. V. I. Charlier, "Wie eine unendliche Welt aufgebaut sein kann", *Arkiv för Matematik, Astronomi och Fysik*, **4**, 1908, 15; "How an Infinite World Might Be Built", *ibid.*, **16**, 1922, 1—34.

Universe.[11] They raised the first cosmological problems even before cosmology became a modern science.

For a long time it was suspected that stars do not fill the Universe uniformly, but form conglomerations or "islands" (Kant, Lambert and others). In the latter half of the 19th century, astronomical opinion was close to admitting the hypothesis of an insular world. The opponents' main argument was the similarity between the galactic objects that were suspected of being islands of stars with planetary galaxies, that certainly lie within the confines of our own stellar system. In 1885, Hartwig announced the discovery of a new star in the Great Nebula in Andromede. The discovery was confirmed by other astronomers.[12] The nova shone with a brightness of up to 5.4 stellar magnitude. Taking into account all the then possible margins of error, the nova from Andromede with such a brightness just had to be inside our Galaxy. It seemed highly improbable that a nearby nova was projected by accident on a faraway galaxy.

When an opinion wins even a seeming victory, it usually finds new arguments to bolster itself. This also happened in this case: the most famous arguments were the measurements of the peculiar motions of the Great Nebula in Andromede. These measurements executed by van Maanen, indicated that the galary shifted approx. 1′ of arc in a year. Attention was also drawn to the fact that spiral galaxies are mainly observed at great galactic latitudes. At the time the shielding effect of inter-stellar matter was unknown and people believed that galaxies really avoided small latitudes. Because it did not seem probable that the position of "insular worlds" would depend on directions derived from our own Milky Way (determined by the plane of our Galaxy), one had to admit that spiral galaxies really are local objects.

Much later, W. Baade and F. Zwicky[13] ascertained that the object of 1855 in the Great Nebula of Andromede was not a nova but a far brighter type of explosion: a supernova. It also became clear, that van Maanen's measurements were plainly wrong; and that the distribution of spiral galaxies in the sky depends on the existence of dark inter-stellar matter in our own Galaxy. In the meantime, however, the adversaries of the insular structure of the Universe were victorious.

This is how the explosion of the supernova of 1885 delayed for some decades to come the development of extragalactic astronomy. Only those scientists who were endowed with great intuition sensed that considering spiral nebulae as local objects does not lead anywhere. This situation is well illustrated by Eddington's views: If we admit—thought he—that the nebulae lie

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[11] See for instance, H. Bondi, *Cosmology*, Cambridge 1960.

[12] For the history of the dispute on the nature of "spiral nebulae" see e. g., O. Struve, *Astronomy of the 20th Century*, London 1962.

[13] W. Baade, F. Zwicky, "On Supernovae", *Proceedings of the National Academy of Sciences*, USA, **20**, 1934, 254.

beyond our stellar system, that they are in reality systems equivalent to ours, then this at least is a hypothesis that can be further developed and studied, to see how it elucidates several problems. From this point of view the theory of "island universes" seems more convenient as a working hypothesis; its consequences are more fruitful, in that they suggest a definite probability of its truth.[14] This matter was of first order importance for the further evolution of cosmology. Information about the distribution of matter in space must be a starting point for any scientific theory of the Universe.

THE BIRTH OF CONTEMPORARY COSMOLOGY

In 1915 appeared Einstein's theory of gravitation (General Relativity Theory).[15] Its application, two years later,[16] to cosmological considerations, was due to the desire to find a way out of the classical paradoxes, as well as to Einstein's own philosophical position. Albert Einstein, as it is known, was under the spell of Spinoza's pantheism.[17] This philosopher held that the World, being identical with God, is its own Creator; is, as it were, a self-creating machine. This process of self-construction happens with logical necessity, all the properties of the World may be deduced from some most general, divine ideas. In Spinoza's pantheism, rationalism climaxed.

Einstein's private inclinations surfaced—more strongly than for many other physicists—in his research. If the World is a self-adjusting machine, then future physical theories should take this fact into account: local physical properties should be induced by the World's global structure. This postulate, when applied to the property of bodies called inertia, was named by Einstein "Mach's Principle."[18] Mach's Principle provided Einstein with the basic intuition that led him to the formulation of General Relativity Theory.

In order to verify if Mach's Principle was in fact realized in the new gravitation theory, one had to reconstruct, with the help of that theory, the global structure of the World (i.e., to build a cosmological model) and to find whether it uniquely characterizes the inertial properties of a text particle.[19]

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[14] A. S. Eddington, *Stellar Movements and the Structure of the Universe*, London 1914, p. 242.

[15] Einstein obtained correct from of the field equations in his work: "Die Feldgleichungen der Gravitation", *Sitzungsberichte der preussischen Akademie der Wissenschaften*, **48**, 1915, 844—847; see also Russian edition of Einstein's complete works: A. Einstein, *Sobranije Naucznych Trudow*, vol. 1, Moscow 1965, p. 448—451 (in the following we shall quote this collection by the abbreviation *SNT*).

[16] A. Einstein, "Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie", *Sitzungsber. preuss. Akad. Wiss.*, 1917, 142—152 (*SNT*, vol. 1, p. 601—612).

[17] See, J. Turek's thesis on Einstein's cosmology and its philosophical fundations (*Kosmologia Alberta Einsteina i jej filozoficzne uwarunkowania*, Lublin 1982).

[18] A. Einstein, "Prinziplielles zur allgemeinen Relativitätstheorie", *Annalen der Physik*, **55**, 1918, 241—244 (*SNT*, vol. 1, p. 613—615).

[19] This was noticed by W. H. Mc Crea, "The Cosmical Constant", *Quarterly Journal of the Royal Astronomical Society*, **12**, 1971, 140—153.

Such was the origin of the "Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie."[20]

All the cosmological predicaments of Newton's Gravitation Theory may be reduced to the question of proper boundary conditions for Poisson's equation. If we admit that at infinity the gravitational potentials have a constant value, relatively to an observer O, and if we suppose that masses are distributed with a spherical symmetry around him (in a world with a uniform distribution of matter any observer sees spherical symmetry), then it follows, from Poisson's equation, that the mean density of matter decreases more quickly than $1/r^2$ (where r is the distance to the observer O) and vanishes at infinity. On the other hand, if we treat the set of stars (= the Universe) as a Boltzmannian gas in the thermodynamical equilibrium, we can show that to finite differences of potential between infinity and the neighbourhood of the observer O, correspond finite ratios between matter density at infinity in space and in the neighbourhood of observer O. Hence the vanishing of density at infinity would imply its disappearance everywhere. This reasoning can be viewed as Einstein's formulation of Seeliger's paradox.

Similar difficulties appear when instead of Poisson's equation we consider the field equations of General Relativity Theory. Guided by Mach's philosophy, Einstein thought that in a consistent theory of relativity there cannot be inertia relative to "space" but only inertia of masses relative to one another. (Einstein's emphasis.) If a given mass is sufficiently far away from other masses in the Universe, its inertia should tend to zero.[21] It turned out, as in the case of Newton's theory, that for a uniform and static repartition of matter there do not exist boundary conditions consistent with that philosophy.

At this point of his investigations, Einstein dodged. If it proves impossible to find good boundary conditions at infinity, then one must get rid of infinity itself. "If it is possible to consider the Universe as a continuum, finite (closed) with regard to its spatial dimensions, then it would no more be necessary to admit any such boundary conditions."[22] Calculations showed that such a static, spatially closed solution exists, but only for the field equations modified by the addition of a cosmological term, just as Neumann's equation is a modification of Poisson's equation. This is how the cosmological constant appeared in the equations. Its appearance in no way violates the conditions imposed by Relativity Theory upon the equation of the gravitational field.

In this following work[23] Einstein expressed his conviction that equations with the cosmological term are superior to those without it, because they do not admit solutions with the energy—momentum tensor equal to zero, $T_{ij} = 0$; a world without matter has no definite geometric structure; in such a world,

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[20] See footnote 16.

[21] *Ibid.*

[22] *Ibid.*

[23] See footnote 18.

according to Mach's Principle, the inertial properties of the test particle are indefinite. Einstain thought that these steps allowed him to overcome the cosmological quandaries of Newton's theory, and to show that the cosmological model of General Relativity Theory is consistent with Mach's Principle. The first belief proved correct, the second one soon turned out false, but continued to simulate creative research.

In his first cosmological work, Einstein tacitly accepted the traditional picture of a World uniformly filled with stars and devoid of systematic movements on a grand scale. Two errors lurked in this conception. First, the World is filled uniformly on the average, not with stars, but with material systems of higher order (such as clusters of galaxies; see further on); second, the World is not a static object. The first error does not bear heavily on the theoretical side of cosmology, it mainly pushes the whole problem one level higher up. The second fault played an important role: Einstein found the only existing static solution, because he did not look for non-static ones. If he were looking for them, he would not have introduced the cosmological constant, for, as it later appeared, there exists a non-static solution with a closed space and the vanishing cosmological constant.[24] Moreover, there exist many non-static solutions with the non-null cosmological constant. One of these solutions was found by Wilhelm de Sitter, shortly after Einstein's first cosmological paper.[25]

In the appendix to the second edition of his book *The Nature of Relativity Theory*, Einstein expressed the opinion that cosmological term would never have been introduced, had the expansion of the Universe been discovered when General Relativity Theory originated. The introduction of the constant seems to Einstein totally unwarranted, once the only reason for which it was introduced disappears.

The irony of events is sometimes startling: de Sitter's solution represents an empty world, with $T_{ik} = 0$. That is how Einstein's hopes to realize Mach's Principle in relativistic cosmology turned to ashes.

De Sitter's model came as a surprise to scientific circles also for other reasons. De Sitter noticed that if one placed in his model an observer and light sources considered as test particles, then the observer would ascertain a diminished frequency for light emitted from sources far away from him; and when, thanks to Weyl's Postulates[26] it became possible to put matter into de Sitter's empty world (or more accurately: movement of matter), one obtained

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[24] See, A. Einstein, *The Meaning of Relativity*, Princeton 1955 (5th edition).

[25] W. de Sitter, "On the Relativity of Inertia. Remarks concerning Einstein's Latest Hypothesis," *Proceedings of the Royal Academy of Sciences–Amsterdam*, **19**, 1917, 1217—1225; "On Einstein's Theory of Gravitation, and Its Astronomical Consequences," *Monthly Notices of the Royal Astronomical Society*, **73**, 1917, 3—28.

[26] H. Weyl, "Zur allgemeinen Relativitätstheorie," *Physikalische Zeitschrift*, **24**, 1923, 230—232.

for the first time an expanding Universe.[26a] Hard to understand—so it seemed. Even de Sitter, an outstanding astronomer, thought the assumption of a static Universe the most natural possibility.

In the meantime, the dispute about the insular distribution of matter in the Universe matured to a conclusion. With the help of the newly built telescope on Mount Wilson, E. P. Hubble resolved the exterior regions of nebulae M31 and M33 into distinct stars; in 1923 he identified the first Cepheid variable in M31, shortly thereafter other Cepheids in M31 and M33. The brightness variability curves of these Cepheids provided a method for measuring the nebulae's distances. No doubt remained that the nebulae were in fact galaxies.

Since 1912, V. M. Slipher was busy measuring the radial velocity of galaxies. M. Humason of Mount Wilson and M. Mayall of Lick Observatory joined this work later on. In 1929, Hubble announced the discovery of a relation (simple proportionality) between the distances of galaxies and the velocities of their escape.[27] From this time on this relation is known as a Hubble's Law. The expansion of the Universe—predicted in de Sitter's model—was supported by observation!

The beginnings of contemporary cosmology remained under the banner of paradoxes; even before it could get rid of prerelativistic paradoxes, new ones made their appearance. The empty expanding Universe of de Sitter was paradoxical. The observed effect of the recession of galaxies also led to embarrasing conclusions: the age of the Universe, calculated from Huble's Law (with the then admitted value of Huble's constant: $H = 500$ km/sec Mpc) proved smaller than, or at best equal to, the age of some astronomical objects. In this case too one spoke of the "Paradox of the Age of the Universe" or the "Expansion Paradox."

In spite of these difficulties, in the second and third decades of our age, cosmology gained two things: an observational basis and a theoretical superstructure. This promoted her to the position of one of contemporary natural sciences. But the distance was still great between observations and theory, and many gaps remained that had to be filled with philosophical constructs.

FURTHER DEVELOPMENT OF RELATIVISTIC COSMOLOGY

Let us make a quick survey of important events in the history of cosmology after the first works by Einstein and de Sitter.

In the years 1922/23, Kornelius Lanczos[28] found a nonstationary linear

[26a] In fact, an expanding character of de Sitter's world model was recognized later on by G. Lemaître, "Note on de Sitter's Universe," *Journal for Mathematics and Physics*, **4**, 1925, 188—192, and by H. P. Robertson, "On Relativistic Cosmology," *Philosophical Magazine*, **5**, 1928, 835—848.

[27] E. P. Hubble, "A Relation between Distance and Radial Velocity among Extra-galactic Nebulae," *Proceedings of the national Academy of Science*, **15**, 1929, 168—173.

[28] K. Lanczos, "Bemerkung zur de Sitterschen Welt," *Phys. Zeits.*, **23**, 1922, 539 – 543; "Über die rotverschiebung in der de Sitterschen Welt," *Zeitschrift für Physik*, **17**, 1923, 168—189.

element for de Sitter's world (the words "static" and "stationary" had still not been made precise, and were used interchangeably); he also studied further properties of this world.

A major advance in the field was achieved by the papers of Alexander Friedman.[29] Adopting the same hypotheses as Einstein or de Sitter concerning the distribution of matter in space, Friedman found two sets solutions for the field equations of Relativity Theory: first (1922) describing a nonstatic universe (that was also nonstationary in today's sense of the word), whose space had a constant positive curvature; a little later (1924) one describing an universe whose space had a constant negative curvature.[30] The papers of Friedman made it clear that Einstein's static model and de Sitter's empty world are limit cases, between which stretches the whole richness of Friedmanian models. In Einstein's static world, evolution has not started yet; de Sitter's world may be viewed as the last phase of an expansion, which led the world to a state with a density of matter that vanishes in the limit. In Friedman's cosmology a new type of variability in time also appeared: the so-called oscillating universes. Different forms of evolution can be obtained in Friedman's models by manipulating the value of the cosmological constant.

In the beginning, Friedman's work did not elicit much interest. Einstein put off his article of 1922 with two notes of a few lines each. In the first note,[31] he attacked Friedman's result as dubious, but in the second one,[32] he confessed that his suspicions were based on an error in his own calculations, and he recognized Friedman's results as "correct and casting a fresh light on the subject." But only much later did Einstein appreciated Friedman's result to the full.[33]

In 1927, Georges Lemaître,[34] who did not yet know Friedman's papers, discovered for the second time Friedman's cosmology. Lemaître's model took into account something which Friedman's model did not consider: besides the cosmic dust which has no effect and a negligible pressure, also the radiation

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[29] A. Friedman, "Über die Krümmung des Raumes," *Zeits. für Phys.*, **10**, 1922, 377—386.

[30] A. Friedmann, "Über die Möglichkeit einer Welt mit knonstanter negativer Kriemmung des Raumes," *Zeits. für Phys.*, **21**, 1924, 326—332.

[31] A. Einstein, "Bemerkung zu der Arbeit von A. Friedmann, 'Über die Krümmung des Raumes'", *Zeits. für Phys.*, **11**, 1922, 326 (*SNT*, vol. 2, Moscow 1966, p. 118).

[32] A. Einstein, "Notiz zu der Bemerkung zu der Arbeit von A. Friedmann, 'Über die Krümmung des Raumes', "*Zeits. für Phys.*, **16**, 1923, 228 (*SNT*, vol. 2, p. 119).

[33] A. Einstein, "Zum kosmologischen Problem der allgemeinen Relativitätstheorie," *Sitzungsber. preuss. Akad. Wissen.* (*phys.-math. kl.*), 1931, 235—237 (*SNT*, vol. 2, p. 349—352).

[34] G. Lamaître, "Un univers homogène de masse constante et de rayon croissant, rendant compte de la vitesse radiale de nébuleuses extra-galactiques," *Annales de la Société Scientifique de Bruxelles*, **47 A**, 1927, 49—59 (English transtaltion of this paper in: *Monthly Notices of the Royal Astronomical Society*, **91**, 1931, 483—490).

with a pressure equal to one third of its energy density (in Friedman models, the pressure equals zero).

Now knowing Lemaître's work, H. P. Robertson[35] found the general form of the metric for space-time (on the basis of its symmetries): it can be decomposed into a universal time and instantaneous spaces that are orthogonal to the time, and that are at every point homogeneous and isotropic. The models of Friedman and Lemaître are but special cases of Robertson's models.

The hitherto achievements of Friedman, Lemaître and Robertson became widely known in Lemaître's version thanks to the authority of Eddington. Sir Arthur Eddington,[36] studying the nonstability of Einstein's static model, understood that the results to which he himself had come were already contained in Lemaître's work. From this time on, Eddington started to publicize a cosmological model (later called the Eddington-Lemaître model) that was monotonically expanding, starting from Einstein's static state. Such a combination of a monotonic model with a static initial state guarantees an infinite timescale ("the natural beginning" as Eddington called it); it allows to eschew the Paradox of the Age of the Universe.

The Eddington-Lemaître model raised a host of new questions: what caused perturbations of density in the initial static state? Why did Einstein's model start to expand rather than shrink? How did the processes develop that were to lead to the origin of galaxies in an originally homogeneous world?

More and more physicists and astronomers started debating on these (and similar) issues; among them: de Sitter,[37] Lemaître,[38] R. C. Tolman,[39]

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[35] H. P. Robertson, "On the Foundations of Relativistic Cosmology," *Proc. Nat. Acad. Sci.*, **15**, 1929, 822—829.

[36] A. S. Eddington, "On the Instability of Einstein's Spherical World," *Monthly Not. Roy. Astron. Soc.*, **90**, 1930, 668—678.

[37] W. de Sitter, "The Expanding Universe, Discussion of Lemaître's Solution of the Equations of the Inertial Field," *Bulletin of the Astronomical Institute of the Netherlands*, **5**, 1930 (no 193), 211—218; "Further Remarks on the Astronomical Consequences of the Theory of the Expanding Universe," *ibid.*, **5**, 1930 (no 200), 274—276; "On the Distance and Radial Velocities of Extragalactic Nebulae, and the Explanation of the Latter by the Relativity Theory of Inertia", *Proc. Nat. Acad. Sci.*, **16**, 1930, 474—488; "Some Further Computations Regarding Non-static Universes," *Bull. Astron. Inst. Netherlands.*, **6**, 1931 (no 223), 141—145; "On the Expanding Universe," *Proc. Roy. Acad. Sci. Amsterdam*, **35**, 1932, 596—607.

[38] G. Lemaître, "On the Random Motion of Material Particles in the Expanding Universe," *Bull. Astron. Inst. Netherlands.*, **5**, 1930 (no 200), 273—274; "The Expanding Universe," *Monthly Not. Roy. Astron. Soc.*, **91**, 1931, 490—501.

[39] R. C. Tolman, "The Effect of the Annihilation of Matter on the Wave-Length of Light from the Nebulae," *Proc. Nat. Acad. Sci.*, **16**, 320—337; "More Complete Discussion of the Time Dependence of the Non-static Line Element for the Universe," *Proc. Nat. Acad. Sci.*, **16**, 1930, 409—420; "On the estimation of Distances in a Curved Universe with a Non-static Element," *Proc. Nat. Acad. Sci.*, **16**, 1930, 511—520; "Discussion of Various Treatments which Have Been Given to the Non-static Line Element for the Universe," *Proc. Nat. Acad. Sci.*, **16**, 1930, 582—594.

G. C. Mc Vittie,[40] W. H. McCrea and Mc Vittie.[41] One should also mention the pioneering work of Tolman[42] on relativistic thermodynamics and its application to cosmology.

The situation had matured enough for surveys to become possible. Those that were the most quoted later were an extensive article by H. P. Robertson, entitled "Relativistic Cosmology;"[43] also Tolman's monograph *Relativity, Thermodynamics and Cosmology.*[44] Both these works, especially Tolman's book, exerted a profound influence on the style of later expositions of relativistic cosmology. They sum up the tradition initiated by Einstein and continued by de Sitter, Friedman, Lemaître and others.

Einstein spoke anew on cosmological matters in 1931.[45] He came to appreciate fully the importance of Friedman's work and under its influence definitely gave up the introduction of a cosmological term into the field equations. The following ideas do characterize his new position: The cosmological term, whose introduction in the equations of the gravitational field is admissible from the point of view of the Theory of Relativity, must however be rejected on account of the postulated simplicity of the theory. Friedman was the first to show that if one admits the dependence upon time of the metric distance between two points, one can obtain a solution to the unmodified field equations, that corresponds to a finite density of matter.[46]

As a consequence of his position, Einstein constructed later models without the cosmological constant. In his aforementioned paper of 1931, Einstein discussed a model with the following characteristics: constant positive curvature of space, zero cosmological constant, zero pressure ($k = +1$, $\lambda = 0$, $p = 0$); this was later called Einstein's model. On a year later, in a paper published jointly with de Sitter,[47] Einstein drew attention to a flat model with zero pressure and no cosmological constant ($k = 0$, $\lambda = 0$, $p = 0$); this was called the Einstein-de Sitter model. This model, on account of its simplicity

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[40] G. C. Mc Vittie, "Condensations in an Expanding Universe," *Monthly Not. Roy. Astron. Soc.*, **92**, 1932, 500—518.

[41] W. H. Mc Crea, G. C. Mc Vittie, "The Expanding Universe," *Monthly Not. Roy. Astron. Soc.*, **91**, 1931, 7—12.

[42] R. C. Tolman, "On the Problem of the Entropy of the Universe as a Whole," *The Physical Review*, Ser. 2, **37**, 1931, 1639—1660; "Non-static Model of Universe with Reversible Annihilation of Matter," *Phys. Rev.*, Ser. 2, **38**, 1931, 797—814; "On the Theoretical Requirements for a Periodic Behavior of the Universe," *Phys. Rev.*, Ser. 2, **38**, 1931, 1758—1771; "Possibilities in Relativistic Thermodynamics for Irreversible Processes Without Exhaustion of Free Energy," *Phys. Rev.*, Ser. 2, **39**, 1932, 320—336.

[43] H. P. Robertson, "Relativistic Cosmology," *Review of Modern Physics*, **5**, 1933, 62—90.

[44] R. C. Tolman, *Relativity, Thermodynamics and Cosmology*, Oxford 1934.

[45] Cf. footnote 33.

[46] A. Einstein, *The Meaning of Relativity*, Princeton 1955 (5th edition).

[47] A. Einstein, W. de Sitter, "On the Relation between the Expansion and the Mean Density of the Universe," *Proc. Nat. Acad. Sci.*, **18**, 1932, 213—214 (*SNT*, vol. 2, p. 396—398).

is often used today as an example in various discussions and numeric computations.

The disputes whether or not to introduce the cosmological constant by no means dried up. The history of this constant is on the one hand too well publicized to be repeated here, on the other hand it carries with it so many obscurities, that it certainly deserves a separate study. Let us adduce here the opinion of Lemaître, which to this day has comparatively the greatest number of supporters.[48] One can prove that the most general expression satisfying the conditions assumed by Relativity Theory for the field equations (i.e. general covariance, zero divergence, linearity with respect to the second derivatives of the metric tensor) is Ricci's tensor, plus cosmological term. Therefore, considerations of generality impose to consider the field equations with the cosmological term. The value of the cosmological constant should be established by comparing theoretical predictions with experiments. In particular, it can turn out that, within the bounds of experimental error, $\lambda = 0$. However, this eventuality is quite different methodologically from the a priori elimination of the cosmological constant from the theory. Discussions on the cosmological constant are still current.[49]

In the thirties, the development of cosmology centred nearly exclusively on its theoretical side. Those who dealt with its relations to observations were mainly de Sitter, Eddington and Tolman. All three of them combined astronomical practice with a profound knowledge of physics and mathematics. From their work—and in certain measure from work of other people also—resulted two important conclusions for cosmology:

1° astronomy is in principle capable of providing cosmology with observational tests necessary to distinguish the model, or a class of models, that most accurately describe the actual world;

2° the observational precision attained at present permits only to affirm that the world is not a static object, but undergoes expansion.

The first conclusion sets cosmology among the empirical sciences, the second one orders to reject a certain model (Einstein's static model) as disagreeing with reality.

THE COSMOLOGY OF LEMAÎTRE

Between the wars, Eddington's conception of a "quiet" beginning (the world starting from Einstein's static state) was rivalled by Lemaître's hypothesis of a brusque start. The only observational criterion with which any conception of a beginning could be confronted, was the Paradox of the Age of the Universe.

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[48] G. Lemaître, *The Cosmological Constant*, in: *Albert Einstein, Philosopher—Scientist*, New York 1957, p. 438—456.

[49] W. H. Mc Crea, "The Cosmical Constant," *Quarterly Journal of the Royal Astronomical Society*, **12**, 1971, 140—153.

In 1931, Lemaître[50] remarked that if one takes as value of the cosmological constant something greater than, but as close as one wishes to, the value characterizing Einstein's static model ($\lambda > \lambda_E$), then for models with a constant space curvature ($k = +1$), one can lengthen at wish the duration of the cosmic evolution, since in the middle stage of such evolution there appears a period of near staticity, which is the longer the less the cosmological constant differs from Einstein's value. The Paradox of the Age of the Universe then no longer exists.

Lemaître's model contains an initial singularity. Not only did he not see any lack of physical "elegance" in this fact, but, he tried to justify ist "naturalness" on the contrary:

> The increase of entropy corresponds to an increase of the number of photons. It thus seems that during thermic as well as radioactive processes, evolution is associated with an increasing number of particles: photons or atoms. This is a new formulation of the principle of degradation of energy: energy is distributed between particles, be they electrons, photons or nuclei, which are ever and ever more numerous. Evolution goes from the simple to the composite, not from a rarefied to a condensed state. The initial state of the world is probably not a primitive nebula, but rather a sort of primitive atom, and the products of its decay from the surrounding world.[51]

The essence of the primordial atom, or primordial nucleus (since its properties are more reminiscent of the nuclear fluid) would consist of its being a state of minimal entropy, in which energy appeared "in as few packets as it is possible."[52]

A philosophy of having simple initial conditions forms the basis of Lemaître's conceptions:

> Cosmogonic theories search for ideally simple initial conditions, from which by the natural interplay of physical forces, the actual world with all its complexity could evolve. It seems difficult to imagine conditions simpler than those that existed when all matter was concentrated in a single atomic nucleus.[53]

> Such a picture finds a natural geometrical support in the point-singularity which arises in Friedman's theory. The radius of space can start from zero. Such singular event which arises when space has a zero-volume is a bottom of space-time which terminates every line of space-time.[54]

Besides these philosophical aspects, Lemaître expanded also on the physical side of his model. In the evolution of the Cosmos, three stages can be distinguished:

1° an abrupt expansion, with the fragmentation of the primordial atom into elementary particles and normal atomic nuclei;

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[50] G. Lemaître, "The Expanding Universe," *Monthly Not. Roy. Astron. Soc.*, **91**, 1931, 450—501.

[51] G. Lemaître, *L'Hypothese de l'Atome Primitif*, Neuchatel 1946, p. 86.

[52] G. Lemaître, *The Primaeval Hypothesis and the Problem of the Clusters of Galaxies*, in: *La Structure et l'evolution de l'Univers*, Bruxelles 1958, p. 6.

[53] G. Lemaître, *L'Hypothese de l'Atome Primitif*, p. 153—154.

[54] G. Lemaître, *The Primaeval Atom Hypothesis...*, p. 7.

2° a quasi-static period, with the formation of condensations: the proto-galaxies;

3° a renewed increase of the expansion rate.

Lemaître, and later G. Gamow and his co-workers,[55] discussed extensively the synthesis of chemical elements from the products of the disintegration of the primeval nucleus; it turned out that in Lemaître's model it is easy to explain the synthesis of heavy nuclei.[55a] Lemaître[56] also studied the condensation of proto-galaxies in the quasi-static period. Mainly due to these works, Bondi[57] could still write in 1952 that Lemaître's model "seems to be the best relativistic cosmology can offer."

THE COSMOLOGY OF MILNE

In the first stage of its development cosmology was exclusively relativistic. The first to question this state of affairs was E. Milne. In a series of works[58] not only did he present his methodology but he constructed a new cosmology, without direct reference to the Theory of Relativity.

In Milne's opinion, the existing theories are of the highest quality, as far as their mathematics is concerned, but their generally admitted interpretations in terms of "expanding space" do cause the highest trouble. Movement as a consequence of a geometry, different from the geometry prevailing in physics, was a credible concept. Gravitation as a deformation of space was a credible concept, though this concept did not contain the faintest allusion as to the nature and origin of gravitation itself; why should the presence of matter exert an influence upon "space" remained unanswered. The mathematical physicists that attribute structure to space, that restore structure to what is structureless, brought back the ether, in fact.[59]

In the period of strong influence of the Vienna Circle, Milne's views on the explanatory functions of physical theory inevitably remained isolated. As the above quotation shows, Milne wanted a theory not only to give mathematical recipes, but also "insight into the phenomena." He must have meant the postulate that the image we make ourselves of the interpreted theory should correspond to the so-called "common sense."[60] One should not forget that in

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[55] See below, the chapter on the problem of the synthesis of chemical elements and the model of the hot universe.

[55a] M. G. Mayer, E. Teller, "On the Origin of Elements," *The Physical Review*, **76**, 1949, 1226—1231.

[56] G. Lemaître, *The Primaeval Atom Hypothesis.*

[57] H. Bondi, *Cosmology*, Cambridge 1960 (first edition in 1952), p. 121.

[58] Results of these works are collected together in two monographs by Milne: *Relativity, Gravitation and World-Structure*, Oxford 1935, and *Kinematic Relativity*, Oxford 1948.

[59] E. A. Milne, *Relativity, Gravitation...*, p. 2.

[60] *Ibid.*, p. 3.

those days the Theory of Relativity was still shrouded in mysticism. Today a number of concepts used by this theory have became stock-in-trade for the theoretical physicist. It is also known that common sense is intimately linked with . . . habit.

Milne's assumptions—in agreement with common sense—were the following: Movements are defined exclusively by kinematic consideration, and are subjected to the requirement that they should be determined by observation, and described in the same manner by observes accompanying particles of the system; the roles of observers with respect to the system should be indistinguishable. The principle of relativity has in fact been used in the form requiring that two observers, remaining in equivalent relations to the whole system, and agreeing to compare their observations (to transform co-ordinates) according to the same rules, should describe the behavior of any particle by the same functions of the same coordinates.[61]

Milne was the first to call this postulate of equivalence of observes "a cosmological principle," and he considered it a new principle of relativity. He tended to think that his principle was more general than Einstein's and that his theory could therefore subsume General Relativity Theory as a special case. This, however, is not the case, the reason being that Milne's theory presupposes the equivalence of simultaneous observes (cosmological principle) whereas General Relativity Theory can be applied to the Universe as a whole also without such strong postulates of symmetry. Its limitation to kinematic considerations is responsible for the appellation of "Kinematic Relativity" that came into use for Milne's cosmology.

In the name of realism, Milne put greater emphasis on transformations from observer to observer than on transformations of co-ordinates. The leading idea of our work—thought Milne—is not the idea of co-ordinates transformation, but the idea of transformation from one observer to another equivalent observer, where the word "equivalent" is to be strictly defined in terms of observations and tests that the observers may effectively perform. The transformations of co-ordinates are but language translations, and are not necessarily relevant to phenomena. An observer can combine his observations in order to obtain co-ordinates of events in an infinite variety of ways, the co-ordinates are but free constructs of the observation.[62] One could ask Milne the teaser: What distinguishes in practice "going over from one observer to another" from a simple transformation of coordinates?

Milne's cosmology introduced yet another novelty. The essence of the cosmological applications of General Relativity Theory consisted in extrapolating local physics to the Universe as a whole. The direction of Milne's

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[61] *Ibid.*, p. 4.
[62] *Ibid.*, p. 5.

reasoning was precisely the opposite. First global assumptions were adopted: Milne's cosmological principle, as well as certain postulates concerning space and time measurements made by equivalent observers. The ambition of Milne was to deduce from such a system the assumptions of the totality of local physics. He only partially succeeded.

The measurement postulates of Milne pertain to the realization of Einstein's operational definitions. Milne takes the sensation of time flowing as a primitive concept in his theory; he concerns himself only with the parametrization of the flow of time (every parametrization is a new clock). However, he proposes to replace Einstein's method of measuring distances by means of a rigid ruler by the method of radar reflection. A change of time parametrization (i.e. the use of another clock) causes automatically a re-scaling of all distances. It is not therefore odd, that we obtain a different picture of the World's evolution if we use an atomic time-scale (an atomic clock), than if we use a dynamic scale (a gravitational pendulum). Milne's contribution to the methodological analysis of time and space measurements are among his lasting achievements.

ROBERTSONIAN AND NEO-NEWTONIAN COSMOLOGY

Milne showed in his investigations that cosmological models can use other approaches than General Relativity Theory. This idea had followers. H. P. Robertson was no doubt influenced by Milne when he came to the conclusion that since cosmological models should be built with a minimum of assumptions, then the dynamic equations of General Relativity should be utilized at the latest possible stage during the model's construction. Inspired by this thought, in 1935, he deduced the general form of metric for space-time: it had a distinguished universal cosmic time that was orthogonal to the spaces with a constant curvature (be it negative, positive or null).[63] The same metric was found independently a year later by A. G. Walker.[64] That is why one often speaks of the Robertson-Walker metric.

It is customary in scientific literature to call all cosmological models that satisfy the (simple) cosmological principle interchangeably Friedman models (or cosmology), or Robertson-Walker models (or cosmology).

This is accurate neither historically nor as a matter of fact. In the terminology used by Robertson, a cosmological model is any space-time, endowed with the Robertson-Walker metric, and fulfilling certain assumptions (borrowed from General Relativity Theory) concerning the movement of particles and light rays. Later on we shall call such models Robertson-Walker

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[63] H. P. Robertson, "Kinematics and World Structure," *Astrophysical Journal*, **82**, 1935, 284—301.

[64] A. G. Walker, "On Milne's Theory of World-Structure," *Proceedings of the Mathematical Society of London*, **42**, (2), 1936, 90—127.

models (cosmology), whereas the models developed by Friedman and later most extensively by Lemaître are those among the Robertson-Walker models that satisfy the field equations of General Relativity; we shall call them of Friedman, or better of Friedman-Lemaître models (cosmology).

In the sequel, Robertson[65] showed that from Robertson-Walker models there result certain testable relationships between observable magnitudes. Robertson's cosmological style found its way into a textbook as late as 1968: a book that was written by his last postgraduate student, T. W. Noonan, on the basis of notes that remained after Robertson's death.[66]

Milne himself, aided by W. H. McCrea,[67] started on a new endeavor: to extrapolate Newton's theory to the Cosmos. This time, also, Relativity Theory served as a guide. It turned out that, if one admits the constant velocity of light and rejects the requirement of a static world, then Newton's gravitation theory, extrapolated to the biggest possible system (assuming homogeneously and isotropically distributed masses) yields in fact the same models as does relativistic cosmology.

THE STEADY-STATE COSMOLOGY AND THE CONSERVATION OF ENERGY PRINCIPLE

All the cosmological theories discussed up to here assumed that the laws discovered by Earth physics apply to the whole of the Universe, and to all stages of its evolution (with the possible exception of the initial singularity); they did this, regardless whether they extrapolated local physics to the world considered globally, or whether they deduced local physics from global assumptions. This basic assumption, though the simplest, does not seem a priori unquestionable. The Universe as a whole may be endowed with properties not possessed by its parts. The first suspicions arose around the global validity of that fundamental law of physics, the principle of conservation of mass and energy. In 1928, J. Jeans formulated the hypothesis that matter may be incessantly created in the nuclei of galaxies; he was suggesting that matter comes into our world from some "totally exterior spatial dimension."[68] Jeans hoped to use this outlandish hypothesis to explain the origin of the spiral structure of the galaxies.

This idea of matter creation in contemporary cosmology is also associated, indirectly, with the name of Eddington; directly with the names of Dirac and Jordan. In his fundamental theory, making use of unconvincing assumptions

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[65] H. P. Robertson, "The Apparent Luminosity of a Receding Nebula," *Zeitschrift für Astrophysik*, **15**, 1935, 69—81; "The Theoretical Aspects of the Nebular Redshift", *Publications of the Astronomical Society of the Pacific*, **67**, 1955, 82—98.

[66] H. P. Robertson, T. W. Noonan, *Relativity and Cosmology*, Philadelphia 1968.

[67] W. H. Mc Crea, E. A. Milne, "Newtonian Universes and the Curvature of Space," *Quarterly Journal of Mathematics* (Oxford), **5**, 1934, 73—80.

[68] J. Jeans, *Astronomy and Cosmology*, Cambridge 1928, p. 352.

and complicated mathematics, Eddington had obtained a series of numerical relationships between physical constants. He saw in these relationships the expression of a fundamental interdependence between the structure of the Universe as a whole and microphysics.[69] From this time on, a new task was bestowed on cosmology: namely to give a more convincing explanation of Eddington's numerical coincidences.

The problem was taken up, and treated differently, by Dirac.[70] He denied any fundamental importance to Eddington's dimensionless constants, considering them as monotonous functions of cosmic time. In particular, the ratio of the mass of the Universe to the mass of the proton ($\varrho c^3 T^3/m_p \approx 10^{39}$), and the ratio between the electric and the gravitational forces acting between a proton and an electron ($e^2/\gamma m_p m_e \approx 2 \cdot 10^{39}$) are seen as functions of the age of the Universe: hence the number of protons (and neutrons) in the Universe should increase proportionally to time squared, whereas the gravitational constant γ should be inversely proportional to time. In the later version of his theory, Dirac[71] abandoned the hypothesis about the growing number of particles, he retained however the variability of constants, formulating it as follows: any two great (i.e., Eddingtonian) dimensionless constants are linked together by simple mathematical relationships, in which coefficients are of the order of magnitude of 1.

Dirac's conception of variable "constants" served as a foundation for the cosmology of P. Jordan.[72] An essential ingredient of this cosmology is the hypothesis of creation of matter. This was introduced in the wake of certain speculations of the author (erroneous by the way), intended to dispose of Olbers's paradox, Jordan did not wish, however, to contradict the law of conservation of matter: so he assumed that new matter appears in such great conglomerations, that the negative gravitational energy associated with it compensates the increase of energy.

The hypotheses of variable constants were received coolly at first. They were viewed as physical speculations at best. In spite of this, the idea of variable constants will appear once more, with a renewed vigor, in the more recent history of cosmology. Similarly, the conception of a perpetual creation of matter turned from a cosmological speculation into a respectable theory, only after Bondi and Gold introduced the so-called ideal (or perfect or strong) cosmological principle.[73]

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[69] A. Eddington, *Relativity Theory of Protons and Electrons*, Cambridge 1936; *Fundamental Theory*, Cambridge 1946.

[70] P. A. M. Dirac, "The Cosmological Constants," *Nature*, **139**, 1937, 323.

[71] P. A. M. Dirac, "New Basis for Cosmology," *Proceedings of the Royal Society*, London, **165 A**, 1938, 199—208.

[72] P. Jordan, *Die Herkunft der Sterne*, Stuttgart 1947; *Schwerkraft und Weltall*, Braunschweig 1955.

[73] Cf. H. Bondi, *Cosmology*, Cambridge 1960.

In 1948, H. Bondi and T. Gold[74] published their steady-state theory of the Universe. This was a deductive theory. The cardinal axiom of this theory was the ideal cosmological principle, which to the postulates of homogeneity and isotropy of space required by the ordinary cosmological principle, added the postulate of stationarity of the world: viz. the image of the Universe is not only independent of the position of the observer in space, but also of the epoch in which the observations are performed.

The ideal cosmological principle proved a deductively strong principle. From this principle and from the observational fact that there is no thermodynamical equilibrium in our immediate astronomic vicinity, there follows directly the hypothesis stating the continual creation of matter *ex nihilo*, and a metric having the same form that the stationary metric of de Sitter's empty model. In the model of Bondi-Gold, matter appears uniformely in space at the rate, as computed by the authors of the theory, one atom of hydrogen per liter of volume every 5.10^{11} years (on the average).

Simultaneously with the publication by Bondi and Gold of their steady--state theory, there appeared in the same journal one after the other two papers by Hoyle,[75] that presented essentially the same picture of the world, but obtained by different, more "relativistic" methods. Hoyle introduced in the field equations of General Relativity a modification analogous to the earlier introduction by Einstein of a cosmological term; but this time it was not a new constant, but a new tensor field, the so-called creation field. Any solution of the field equations so modified tends asymptotically to de Sitter's stationary metric. The creation field makes the divergence of the matter tensor unequal to zero, so that the conservation principles in their usual sense are no longer respected.

The sharp controversies, concerning the scientificity of the Bondi-Gold--Hoyle theory, became progressively diminished, especially in view of the fact that the steady-state cosmology proved particularly amenable to empirical testing.[76]

THE DEVELOPMENT OF RADIOASTRONOMY

After the emergence of the steady-state theory of the Universe, it seemed that the ingenuity of the theoreticians had been exhausted. Physicists were inclined to view General Relativity as a closed theory, whereas the development of the observational technology did not foster hopes of the

[74] H. Bondi, T. Gold, "The Steady-State Theory of the Expanding Universe," *Monthly Not. Roy. Astron. Soc.*, **108**, 1948, 252—270.

[75] F. Hoyle, "A New Model for the Expanding Uniwerse," *Monthly Not. Roy. Astron. Soc.*, **108**, 1948, 372—382; "On the Cosmological Problem," *Monthly Not. Roy. Astron. Soc.*, **109**, 1949, 365—371.

[76] M. Heller, "'Stwarzanie' Materii jako prawo fizyki," *Roczniki Filozoficzne*, t. 14, 1966, s. 93—98.

models being tested soon. Cosmology came more and more to be regarded as a discipline into which a full-blooded physicist or astronomer should venture only after work-hours, for the sake of mental relax.

An indication of better times to come was given by the revision of Hubble's constant, made by Baade and Sandage. It appeared that the old calculation of Hubble's constant rested on a faulty estimate of the distance to the nearest galaxy. The new measures reduced the value of Hubble's constant to 75 km/sec Mpcs, which increased the age of the Universe and canceled the expansion paradox.[77]

A radical change of this unsatisfactory situation came from the least expected side. Even in the worst times one could detect augures of betterment. In 1932, Karl Jansky announced the first recording of radio-waves from beyond Earth. During World War II, Jansky's works were continued by one man: Grote Reber, who drew up the first radio-maps of the sky. World War II caused quite unexpectedly the development of a new science; radioastronomy. The demobilized radar installations with a trained staff became the nucleus of future radio-observatories.

In a short time radioastronomy became one of the fastest growing observational disciplines. In 1950, M. Ryle and his associates from Cambridge published a catalog containing 50 radio sources: that was the first Cambridge Catalog (1C). Five years later, also under Ryle's supervision, the catalog 2C was published: it contained 1936 radiosources. The following catalog, 3C, contained less sources (471), but they were located with a far better precision. The version of 3C, corrected by A. S. Bennett in 1959, contains a practically complete array of radiosources of the northern hemisphere (between declination $-5°$ and $+90°$), brighter than 9 units of flux (1 unit of flux $= 10^{-26}$ Em^{-2} Hz^{-1}) on a frequency of 178 Hz. The later catalogs indicate an increasing sensibility of detection. The catalog 4C contains sources brighter than 2 units of flux; the next one (5C) sources brighter than 0.01 units of flux (on a frequency of 408 MHz). For the southern hemisphere, the most important are the catalogs produced in Australia in the years 1958—1961, especially the well-known catalog from Parkes radioobservatory. For obvious reasons we cannot list here all the radio catalogs of the sky.[78]

Parallelly to the cataloging of radiosources work progressed on their identification with optical objects. During this work, W. Baade and R. Minkowski noticed that the source Cygnus A is identical with the brightest galaxy belonging to a dim cluster in this constellation. It turned out that the radiooutput of this radiosource is about 10,000,000 times stronger than the radio-output of ordinary galaxies (it is approx. 10^{45} erg. sec^{-1}). Sources of this

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[77] Cf. P. J. E. Peebles, *Physical Cosmology*, Princeton 1971, chapter 2.

[78] See, for example, M. Ryle, "The Counts of Radio Sources," *Annual Review of Astronomy and Astrophysics*, **6**, 1968, 249—266.

type—more were to be discovered later—were named radiogalaxies. The huge energy sources of these radiogalaxies remain an open problem.

It was established already in 1960 that the angular dimensions of some of the optic objects identified as radiosources are very small. In 1963, at the Parkes Observatory, it was possible to localize source 3C 273 with a precision of up to one hundredth of a second of arc—taking advantage of the hiding of this object by the Moon, that could be seen three times that year in Parkes. It was shown that this was a double radiosource; Its *B* component was optically resembling *a* (punctiform) star. Later more objects of this type were discovered; they were called quasi-stellar objects, quasars for short.

In the beginning one could not decode the spectrum of quasars. After intensive study it became clear that this inability was due to a pronounced shift to the red. For quasar 369, for example, the shift is 2,012! If such enormous shifts are to be interpreted in accordance with Doppler's effect, then Hubble's law puts the quasars at (cosmologically) immense distances and their energetic supply remains a riddle to be solved.

A discussion whether to adopt a local, a cosmological or some intermediate explanation of these red shifts would require a separate survey.[79] The first attempts to sum up all radiosources for the sake of cosmological testing were undertaken by M. Ryle and P. A. G. Scheuer in 1955 on the content of 2C. The very controversial results of this summing up were unfavorable to the steady-state theory.

Theoretically, for a static Universe, the graph of the function $\log N(S) - \log S$ should be a straight line with slope $-3/2$; here $N(S)$ indicates the number of radiosources in a unit solid angle, such that the flux density on a given frequency surpasses S.[80] Taking into account the spectral red-shift, the curve should flatten out, but the empirical curve obtained by Ryle and Scheuer gets steeper on the contrary (inclination of -3, which indicates an excess of sources both distant and weak, with respect to the static model). This anomaly was confirmed by counts made by Mills, Slee and Hill from 1958 on the content of the Parkes catalog (inclination $= -1.8$). More recent results obtained on the 5C catalog by Ryle and G. G. Pooley give also an inclination of -1.8, but for little values of the flux density they show an unexpected flattening out of the curve.[81] Two explanations are possible: one can admit either that radiosources are not evenly distributed in space, or that they undergo a very rapid evolution: at great distances we would systematically observe radiosources at a very early stage. The first possibility cannot be reconciled with the fact that the position of

[79] Cf. D. W. Sciama, *Modern Cosmology*, Cambridge 1971; P. J. E. Peebles, *Physical Cosmology*, Princeton 1971.

[80] In non-stationary models, the apparent dimming of sources, resulting from the red-shift, is more marked than the increasing density of sources with distance, which is solely due to expansion. Therefore, in stationary models, one should expect diminishing the radiosources density with distance as compared with static model.

[81] Cf. footnote 78.

the observer from Earth is not a privileged one; the second possibility contradicts the steady-state cosmology.

THE PROBLEM OF THE SYNTHESIS OF CHEMICAL ELEMENTS AND THE MODEL OF THE HOT UNIVERSE

The works of Lemaître, and Gamow & Teller, referred in preceding sections, started a new field in the study of cosmology. From this time on, the ambition of any more thoroughly worked out cosmological model was to explain the abundance of chemical elements in the Universe, as we presently observe it. Following Lemaître, scientists associated the synthesis of elements from hydrogen with superdense initial states in the history of the Universe. In 1948, Alpher, Bethe and Gamow created a theory,[82] dubbed after the author's names Alpha-Beta-Gamme Theory, which was to rival Lemaître's theory of the primeval nucleus; the latter theory—we may remember—could explain the synthesis of heavy nuclei, but had trouble with the lighter ones. According to the ΑΒΓ theory, the initial state of the Universe was a mixture of neutrons and radiation at high temperature and under high pressure, which the authors of the theory baptized "primeval 'ylem." As the Universe expanded, the pressure fell, neutrons metamorphosed into protons under reaction. The chain of succesive catchings of neutrons and reaction was to lead to the actual proportions among the existing chemical elements. The 'ylem theory was developed later in a series of papers by Alpher and Hermann.[83]

Unfortunately, if one takes account of the newest data on the existence of the so-called isotropic background radiation and on the average density of matter in the Universe, the ΑΒΓ theory is no longer capable of elucidating the synthesis of elements heavier than helium (except a little bit of lithium and some other light elements).[84]

The problem of the cosmological synthesis of nuclei was also attacked from other sides.[85] There did exist theories on the appearance of nuclei in initial states, characterized by thermodynamic equilibrium, or in an environment of charged particles,[86] or in an environment of neutrons;[87] there was Zeldowicz's theory of the "cold big bang," which differs from ΑΒΓ theory in that, that for superdense initial states the temperature of 0° K is assumed;

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[82] R. A. Alpher, H. Bethe, G. Gamow, "The Origin of Chemical Elements," *Phys. Rev.*, 73, 1948, 803—804.

[83] For a survey of these works consult: D. W. Sciama, *Modern Cosmology*, Cambridge 1971; J. E. Peebles, *Physical Cosmology*, Princeton 1971.

[84] *Ibid.*

[85] See an excellent review paper on the synthesis of chemical elements: B. Kuchowicz, "Problemy i osiągnięcia astrofizyki jądrowej," *Postępy Fizyki*, I: **22**, 1971, 495—509; II, **22**, 1971, 601—622 (in Polish).

[86] *Ibid.*

[87] *Ibid.*

however, none of these theories can pride itself on any lasting success in explaining the abundance curve.[88]

Continually new theories and quandaries made people wonder whether to treat the initial superdense states as a melting-pot in which the elements were synthesized once and for all; was not just a blind-alley? The more so that in the steady-state theory of the Universe there are no periods of superdensity; the synthesis in that case has to be explained differently anyway. Another such melting-pot could be furnished only by the interior of stars: a number of authors made a positive contribution to the problem of nucleosynthesis in this way: they were E. M. Burbidge, G. R. Burbigde, A. Fowler and Fred Hoyle, in the paper: *Synthesis of the Elements in Stars*, commonly cited as B^2FH.[89] The paper unleashed a torrent of further studies, containing more and more detailed results. The synthesis of nuclei in the interior of stars from primeval hydrogen could elucidate the dissemination of all elements, with the exception of helium. Later data would allow stars of our Galaxy to produce a maximum of 10% of the observed quantity of helium. As the inadequacy of the theory of stellar nucleosynthesis, as far as the synthesis of helium is concerned, is now beyond question, there was no other course open then to revert to the theory of nucleosynthesis in the superdense initial state. The impossibility to explain the synthesis of elements heavier than lithium by the ABΓ theory became now an argument in favor of that theory; the ABΓ and B^2FH theories made a coherent whole: elements up to helium were created in a hot Big Bang, elements heavier than helium—in the interior of stars.[90]

THE ISOTROPIC BACKGROUND RADIATION AND THE HOT MODEL OF THE UNIVERSE

The original formulation of the ABΓ theory, in 1948, allowed a certain possibility of experimental testing. The theory predicted the existence of an isotropic radiation field (the so-called background radiation) at a temperature of about 25° K, as a relict of an earlier, radiational, era in the history of the Universe. In a later, amended, version of the ABΓ theory, the value of the present temperature of the background radiation was corrected to approx. 6° K.[91] The radioastronomical technology of the time did not permit to confront these predictions with observations. This became possible only in the sixties.

The history of the discovery of this residual radiation is fairly well known. By the end of 1964, R. H. Dicke was working on an apparatus especially suitable to pick up this radiation. At the same time, two research workers from

[88] The original contributions are quoted in the works enumerated in footnotes 83 and 85.

[89] "Synthesis of the Elements in Stars," *Review of Modern Physics*, **29**, 1957, 547—650:

[90] Cf. D. W. Sciama, *Modern Cosmology*; S. Weinberg, *Gravitation and Cosmology*, New York—London 1972, p. 545—561.

[91] Cf. G. Gamow, *Vistas in Astronomy*, London 1959.

the Bell Telephone Laboratory, A. A. Penzias and R. W. Wilson, studying the noise of some of telecommunication devices, found by pure chance the remnants of an unknown radiation. Dicke immediately suggested that this could well be the residual radiation after the primeval explosion of the Universe. Other institutes quickly joined these investigations. Here are some of the main results:

1964: Penzias and Wilson (Holmdel, New Jersey) establish on wavelength 7 cm the existence of a radiation at temperate 3.5° K; a greater precision somewhat later gave 3.1° K$\pm$1° K.

1966: P. G. Roll and D. T. Wilkinson (Princeton): wavelength 3 cm, temperature 3.0$\pm$0.5° K.

a little later: T. F. Howell and J. R. Shakeshaft (Cambridge): wavelength 21 cm, temperature 2.8$\pm$0.6° K.

All these results indicated with a notable precision the isotropy of this radiation. On top of this came the studies on interstellar molecules of cyanogen (CN). These molecules are in an excited state, as if they were continually exposed to a radiation at 3° K.[92]

The latest measurements point to isotropy with a precision better than 3% and to a temperature of 2.7$\pm$0.2° K.[93] The radiational spectrum of the black body at this temperature shows a clearcut maximum at the vicinity of 1 mm. If observational points in that region of the graph are obtained, they will be a decisive argument that this radiation truly is the radiation of a black body; but because the atmosphere shields waves of length close to 1 mm, the crucial experiment cannot be performed on the surface of the Earth.[94]

Background radiation is, together with red-shift, the most effective observational test to date. First of all it is a strong argument in favor of the evolutionary model with a superdense initial state (hence originated the imaginative term: primordial fireball radiation). Present-day measurements of the background radiation allow to calculate the magnitude $s = S/n$ (entropy per baryon) for early stages of the world's evolution; this in turn yields important information on the course of physical processes. This information is strongly selective with respect to different theories of cosmic evolution. Present data do not run counter to the predictions of the "hot" model of the Universe, which constitutes a modern version of the ΑΒΓ theory. The theory of the steady-state Universe lost its appeal: in its original version it cannot explain the origin of the backgroung radiation. Attempts have been made to so modify the theory that the background radiation could fit within it:[95] but these *ad hoc*

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[92] More data see, D. W. Sciama, *Modern Cosmology*, pp. 176—186; P. J. E. Peebles, *Physical Cosmology*, pp. 131—136; S. Weinberg, *Gravitation and Cosmology*, pp. 506—528.

[93] *Ibid.*

[94] *Ibid.*

[95] J. V. Narlikar, N. C. Wickramasinghe, "Microwave Background in a Steady—State Universe," *Nature*, **216**, 1967, 43—44.

endeavours have elicited little response of the scientific opinion. Background radiation is also a strong test for the isotropy of the Universe on a grand scale. Much attention has been paid to the assessment of this isotropy and its cosmological implications.[96]

The isotropy of the background radiation confirms the Friedmanian character of cosmic evolution. This result also agrees with the research in extragalactic astronomy. The question centers on a dispute about the existence of higher-order clusters of galaxies. One group of extragalactic astronomers (G. O. Abell, G. de Vaucouleurs) deems the existence of second-order clusters of galaxies as highly probable, another group (F. Zwicky, K. Rudnicki, M. Karpowicz) thinks that if one considers distances of the order of 40 Mpc, the world can be treated as roughly isotropic, with contingent, local, density fluctuations (which the other group takes as second-order clusters).[97]

The "hot" model of the Universe has been the subject of many papers. The big problem is how to fill the Friedmanian cosmological model with physical processes that led the world from the primordial, hot big bang to the state that we observe today. Of special interest is the applicability of General Relativity at instants close to the singularity.[98] One talks of the so-called threshold epoque, starting from which relativistic cosmology is valid; before it quantum gravitational effects played a decisive role.[99] Proposals have been made to create a quantum cosmology.[100]

H. Alfvén and O. Klein raised the issue of antimatter in cosmology. In 1962, they created a new cosmological theory,[101] in which they postulated the world's symmetry with respect to matter and antimatter; they presented the mechanisms which in the early stages of the world were to lead to the separation of matter from antimatter.[102] It appeared that antimatter could also be introduced into the hot model; what is more, a satisfactory method of separation of matter and antimatter can be given in this model.[103]

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[96] Cf. M. Heller, Z. Klimek, K. Rudnicki, *Observational Foundations for Assumptions in Cosmology*, in: *Confrontation of Cosmological Theories with Observational Data* (Symposium of the International Astronomical Union, No 63), 1974.

[97] For a modern re-treatment of these problems consult the monograph: P. J. E. Peebles, *The Large-Scale Structure of the Universe*, Princeton 1980.

[98] See, for example, R. Omnès, "Le rôle des particules élémentaires en cosmogenèse," *Annales de Physique*, **4**, 1969, 515—542.

[99] See, J. B. Zel'dovich, I. D. Novikov, *Relativistic Astrophysics*, Moscow 1967 (in Russian).

[100] For newer developments of the subject consult review-papers published in the following volumes: *General Relativity—An Einstein Centenary Survey*, ed. by S. W. Hawking and W. Isreal, Cambridge 1979; *General Relativity and Gravitation—One Hundred Years after the Birth of Albert Einstein*, vol. 1 and 2, ed. by A. Held, New York—London 1980.

[101] Cf. H. Alfvén, *Wärlden–Spegelvärlden Kosmologi och Antimateria*, Stockholm 1966.

[102] H. Alfvén, "Symmetric Cosmology," *Nature*, **299**, 1971, p. 184.

[103] See for example, D. J. Raine, *The Isotropic Universe*, Bristol 1981, pp. 234—236.

Another important issue for the evolutionary model is how galaxies originated in it.[104]

Despite the many blanks that persist in the evolutionary model of the hot Universe, it is still considered the most promising.[105]

OTHER DIRECTIONS OF RESEARCH

In contemporary physics theory and experiment are closely knit together. This association is quite clear in cosmology. In the methodology of all the cosmologically significant measurements, an important role is devoted to signal theory, and to the theory of the space in which the signal gets propagated. Therefore all the advancements mentioned above are to be viewed as achievements of both a theoretical and observational nature. These achievements stimulated research work in the theory of the Universe. The bad years of Cosmology are now over.

First of all, General Relativity ceased to be regarded as closed for further research. The renewal of studies in this area in the last years should receive a separate study; let us only mention a few directions of possible importance for the applications of cosmology.

First of all a great development of the mathematical methods used in relativistic physics. The progress is twofold:

1° more and more branches of mathematics are made use of in the service of Relativity;

2° Relativity itself is given a more sophisticated treatment.[106]

A completely new area of applications of General Relativity was opened by work on the gravitational collapse. Pioneering work there dates from before the war,[107] but it is only when the collapse was used to describe certain stages in the evolution of specific astronomical objects (neutron-stars, quasars), that concrete results were gained.[108] One can speak today of a new relativistic

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[104] After the completion of the present paper many advances in this subject have been made. Even a listing of main results and methods would require a seperate article. The only thing we can do now is to refer the reader to the existing literature such as for example: P. J. E. Peebles, *The Large-Scale Structure of the Universe*, Princeton 1980.

[105] See for instance, S. Weinberg, *Gravitation and Cosmology*; D. J. Raine, *The Isotropic Universe*; D. W. Sciama, *Modern Cosmology*.

[106] As "samples" of this approach see for instance: J. K. Beem, P. E. Ehrlich, *Global Lorentzian Geometry*, New York—Basel 1981; *Differential Geometry and Relativity*, ed. by M. Cahen and M. Flato, Dordrecht—Boston 1976; R. K. Sachs, H. Wu, *General Relativity for Mathematicians, New York–Heidelberg–Berlin, 1977.*

[107] See for example: S. Chandrasekhar, *Introduction to the Study of Stellar Structure*, Chicago 1939.

[108] Probably the first work on the collapse in this context can be attributed to F. Hoyle, W. A. Fowler, G. R. Burbidge and E. M. Burbidge, "On the Relativistic Astrophysics," *Astrophysical Journal*, **139**, 1964, 909—928.

science on the boundary between theoretical physics and astrophysics.[109] The problem of half-closed worlds, associated with the collapse, find application within both relativistic astrophysics and cosmology.[110] Many issues pertaining to the collapse can be automatically transposed to be phenomenon of expansion of the Universe (anticollapse), or to the period of contraction in oscillating models.

The concept of collapse is mainly employed to investigate the final evolutionary stage of stars with a mass greater than critical mass ($\approx 2M_{\odot}$). Stars with a mass between $1.2M_{\odot}$ and $2M_{\odot}$ finish their evolutionary cycle as neutron-stars. In the theory of neutron-stars endowed with great densities relativistic corrections have also to be made. Today we know that neutron--stars appear to us as pulsars. It seems highly probable that to solve the enigma of the physical nature of quasars, relativistic gravitation theory will have to be used. These (and other) problems fall into the realm of relativistic astrophysics, a new and dynamically evolving area of relativistic applications.[111]

J. Weber's report about the recording of gravitational waves caused a great sensation in relativistic physics.[112] This discovery, if confirmed, will serve as another experimental test of General Relativity; it is important from a theoretical point of view, in the question of energy transfer in General Relativity;[113] it is quite possible that it contains information relevant to cosmology.

There is no one nowadays to think that in astrophysical and cosmological applications one could go back to pre-Relativity times. On the contrary, there are those who think that one should go over from General Relativity Theory to theories more general still. The best known attempt in this direction is the scalar-tensor gravitation theory of Brans and Dicke,[114] in which, besides the usual metric field, one introduces a scalar field, conjugate with the first and accounting for the variability of the gravitational constant. This goes back in a sense to the old theories of Dirac and Jordan. The departure from orthodox Relativity Theory, foreseen by the theory of Brans-Dicke, should become apparent mainly in some stages of the evolution of stars and galaxies, as well as

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[109] See for example: *Black Holes, Gravitational Waves and Cosmology: An Introduction to Current Research*, ed. by M. Rees, R. Ruffini and J. A. Wheeler, New York—London—Paris, 1974.

[110] Cf. V. Trimble, "Supermassive Objects in Astrophysics," *Nature*, **232**, 1971, 607—611.

[111] Cf. footnote 109.

[112] A survey article on gravitational radiation: D. W. Sciama, "Recent Developments in the Theory of Gravitational Radiation," *General Relativity and Gravitation* (*Journal*), **3**, 1972, 149—165. See also: J. Weber, *The Search for Gravitational Radiation*, in: *General Relativity and Gravitation—One Hundred Years...*, vol. 2, pp. 435—467.

[113] Remarks on the subject can be found in: A. Trautman, *Conservation Laws in General Relativity*, in: *Gravitation*, ed. by L. Witten, New York 1963, 169—198.

[114] C. Brans, R. H. Dicke, "Mach's Principle and Relativistic Theory of Gravitation," *Phys. Rev.*, **124**, 1961, 925—935.

in the cosmic scale.[115] Other attempts to generalize General Relativity Theory are also known.[116]

Current advancements of orthodox relativistic cosmology mainly consist in the working out of non-Friedmanian models. It is obviuos that the assumptions of a homogeneous and isotropic distribution of matter are but gross approximation of what actually takes place.[116a]

To reject homogeneity creates grave mathematical difficulties. In 1946 already, E. Lifshitz[117] studied non-homogeneous approximate solutions to the field equations in connection with the problem of stability of homogeneous models. A. Raychaudhuri,[118] obtained a general theorem on non-homogeneous models. W. Bonnor obtained solutions with a spherical symmetry that at great distances from the center of symmetry automatically coincides with Friedman's models.[119] Lately E. Saar[120] has shown that field equations may be partitioned in two: one part describes the evolution of in homogeneities, the second part the evolution of homogenity. This second part is a generalization of the usual equations for a homogeneous world, with a term pertaining to inhomogeneity. After the necessary averaging is done, this term can be regarded as effective energy-momentum tensor, representing the feedback between inhomogeneities and the global dynamics of the Universe. Inhomogeneities appear in the world's dynamics in the form of negative pressure.

Rejection of the isotropy assumption allows one to consider rotating worlds. The first anisotropic, rotating cosmological model was constructed by Kurt Gödel[121] in 1949; the model had closed timelike curves; Gödel obtained a number of theorems on such models.[122] Other anisotropic solutions were

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[115] R. H. Dicke, *Implications for Cosmology of Stellar and Galactic Evolution Rates*, in: *Relativity, Groups and Topology*, p. 258—307.

[116] See, S. Weinberg, *Gravitation and Cosmology*, p. 611—633.

[116a] See, M. MacCallum, *The Mathematics of Anisotropic Spatially-Homogeneous Cosmologies*, in: *Physics of the Expanding Universe*, ed. by M. Demiański, Berlin—Heidelberg—New York 1979, p. 1—59.

[117] E. Lifshitz, "On the Gravitational Stability of the Expanding Universe," *Journal of Physics, USSR*, **10**, 1946, 116.

[118] A. Raychaudhuri, "Relativistic Cosmology," *Phys. Rev.*, **98**, 1955, 1123—1126.

[119] Cf. O. Heckmann, E. Schüsking, *Relativistic Cosmology*, in: *Grativitation*, p. 438—469 (447—448).

[120] E. Saar, "Inhomogeneous Model Universes, I. Basic Equations, II. Gauge Invariance, III. Lorenz Gauge," *Tartu Astrofüsika Observatooriumi Publikatsioonid*, **39**, 1971, 206—233, 234—248, 249—272.

[121] K. Gödel, "An Example of a New Type of Cosmological Solutions of Einstein's Field Equations of Gravitation," *Review of Modern Physics*, **21**, 1949, 447—450.

[122] K. Gödel, *Rotating Universes in General Relativity Theory*, in: *Proceedings of the International Congress of Mathematicians 1950*, vol. 1, Cambridge Mass.., 1952, p. 175—181.

found by: B. P. Kompaneets and A. S. Chernov,[123] R. Kantowski and P. K. Sachs.[124]

The wealth of cosmological models built lately, that have interesting mathematical or physical properties, is so great that they couldn't even be mentioned here.[125]

For a number of years a moot point in cosmology was that of the initial singularity that appears in many models of the Universe. One may think that the desire to get rid of this singularity was responsible for the creation of the steady-state cosmology. The last years brouht an undeniable progress in that area.

Initially one thought that the singularity appears as a consequence of simplifying assumptions that impose excessively strong symmetries on the model.[126] This view was expressed, among others, by L. Landau and E. Lifshitz in their well-known textbook.[127] But it was soon proved wrong.

The first theorems on the existence of a singularity without symmetry assumptions was obtained by R. Penrose,[128] S. W. Hawking,[129] R. P. Geroch.[130] According to these theorems, the singularities do not result from simplifying assumpions, but are the consequences of postulates of a very general nature, the rejection of which causes the physical unsoundness (e.g. big negative pressure) of gravitation theory. In 1970, Hawking & Penrose[131] proved a very general theorem, from which it results, that singularities are unavoidable: 1° when a single heavenly body collapses, 2° at the occasion of collapse or anticollapse (expansion) of the Universe as a whole, 3° in cosmological models with a closed space. The theorem of Hawking-Penrose was proved only when the cosmological constant $\lambda > 0$, but there are hints that it holds also for $\alpha = 0$.[132]

B. A. Bielinskiy, E. M. Lifshitz, N. M. Khalatnikov[133] were forced to

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[123] B. P. Kompaneets, A. S. Chernov, *Solution of Gravitational Equations in an Homogeneous Anisotropic Model*, in: *Gravitational Conference*, Tbilisi 1965, p. 118—120.

[124] R. Kantowski, *Some Relativistic Cosmological Models, Thesis*, University of Texas, 1966; R. Kantowski, R. K. Sachs, "Some Spatially Homogeneous Anisotropic Relativistic Cosmological Models," *Journal of Mathematical Physics*, 7, 1966, 443—446.

[125] See the fundamental monograph: D. Kramer, H. Stephani, E. Herlt, M. MacCallum, *Exact Solutions of Einstein's Field Equations*, Cambridge 1980.

[126] See, R. C. Tolman, *Relativity, Thermodynamics and Cosmology*, 438—439.

[127] L. Landau, E. Lifszic, *The Classical Theory of Fields*, Massachussets 1962, p. 397.

[128] R. Penrose, "Gravitational Collapse and Space-Time Singularities," *Physical Review Letters*, **14**, 1965, 57—59.

[129] S. W. Hawking, "Singularities and the Geometry of Space-Time, Adams Prize Essay; The Occurance of Singularities in Cosmology," *Preceedings of the Royal Society*, **300 A**, 1967, 187—201.

[130] R. P. Geroch, "Singularities in Closed Universes," *Phys. Rev. Lett.*, **17**, 1966, 445—447.

[131] S. W. Hawking, C. F. R. Ellis, *The Large Scale Structure of Space-Time*, Cambridge 1973.

[132] S. W. Howking, R. Penrose, "The Singularities of Gravitational Collapse and Cosmology," *Proc. Roy. Soc.*, **314 A**, 1970, 529—548.

[133] B. A. Bielinsky, E. M. Lifshitz, N. M. Khalatnikov, "Oscillatory Regime of the Approach to the Singularity in Relativistic Cosmology," *Uspiekhi Phys. Nauk*, **102**, 1970, 463—500 (in Russian).

revise their earlier views; they employed an original method. It is well-known that in the general solution of the field equations there should appear 4 freely chosen functions of the co-ordinates in the case of empty space, and 8 such functions in the case of space filled with matter. To get a solution with such properties, the above authors utilized the so-called generalized solution of Kasner; there appear in it 3 resp. 7 freely chosen functions of the co-ordinates, for the absence or presence of matter in space, retrospectively, the solution is therefore wellnigh general. To obtain the one missing function, one introduces small perturbations in Kasner's equation. The more general solution obtained in this way does indeed have a singularity.

CONCLUSIONS

Let us emphasize once more than the present survey of the recent achievements of cosmology was done selectively according to the author's personal interest and has no claim to completeness. Yet even such a subjective look on the development of the contemporary science of the Cosmos allows one to draw certain conclusions:

1° The creation of contemporary cosmology was made possible by two things: (i) the development of an observational base (the insular distribution of matter in space, the discovery of the red-shift in galactic spectra); (ii) the existence of a coherent theory suitable for cosmological extrapolations (General Relativity).

2° The great distance between the observational base and theoretical constructs was responsible for the interference of private opinions (of a philosophical character) in cosmology itself; in the beginning cosmology developed not only owing to the confrontation of theoretical predictions with observations, but rather due to the so-called cosmological paradoxes.

3° The successes of General Relativity in the field of cosmology in its first period lay mainly in the construction of models of the Universe. Other cosmological theories, even if not directly dependent of General Relativity, did however, consciously or unconsciously, mimic it.

4° The dramatic improvement of several observational techniques (especially radioastronomical ones), in the late fifties and early sixties made it necessary, on the one hand, to take advantage of cosmological theories in order to properly interpret the results of the observations; they created, on the other hand, a favorable climate for the development of theoretical ideas.

5° The evolution of theory and observational base metamorphosed cosmology itself. Some years ago "cosmology" started to look for some global solutions of certain relativistic field equations, or studied their properties. Today "cosmology" means physics on a suprastellar scale with respect to space as well as time. Its main task is to explain the existence and history of all the objects in the sky, starting with cosmic particles (including photons), through cosmic dust, planets, stars and star clusters, and ending with galaxies and their clusters.[134] Another author[135] compares the transformation of the science of the Universe from a cosmological kinematics to a cosmological physics, to the mutation of astronomy from "heavenly mechanics" to astrophysics.

6° One could introduce another terminological distinction: to reserve the name "cosmology" for the study of the structure and evolution of the Universe as a whole, on the grandest scale, and to call "cosmogony" all the attempts to reconstruct the genesis and history of specific material systems—be they elementary particles, atomic nuclei, clusters of galaxies, galaxies, stars, etc. ... Cosmology is considered as more basic than cosmogony, in the sense that, in accordance with present methods, cosmogonic studies must be pursued on the "canvas" of cosmological results. Cosmology constructs models of the Universe, and cosmogony fills them with physical processes (though very often the canvas, together with the physical processes filling it, is also called a model). Cosmology could be defined as the geometry of the Universe in a broad sense. "Geometry" has in this context to be understood the way Einstein did it, i.e. as the geometrization of certain physical magnitudes. One could also use the vivid expression attributed to Wheeler: "geometrodynamics of the Universe."

7° Owing to these mutations of the contemporary science of the Cosmos, the necessity to supplement them with philosophy has vanished, or at least has been considerably reduced.[136]

8° One suspects that the distance between observations and theory will be further reduced, and that the transformations of the science of the Cosmos will go still further in the direction indicated, once results obtained by observatories beyond the atmosphere will start coming in. We are just witnessing the birth of this observational technology.

The history of modern cosmology offers an interesting case study in the history of science. "By now, cosmology has developed far beyond the stage of a fascinating parlor game, in which the rules are fixed by common agreement among the participants, inaccessible to empirical verification."[137] During the lifetime of two generations it has earned the status of an exact empirical science.

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[134] Cf. W. Kundt, *Survey of Cosmology*, preprint.

[135] M. von Reinhardt, "Contemporary Problems of Cosmology," *Usp. Phys. Nauk*, **105**, 1971, 125—141 (in Russian).

[136] Cf. G. F. R. Ellis, "Cosmology and Verifiability," *The Quarterly Journal of the Royal Astronomical Society*, **16**, 1975, 245—264; M. Heller, M. Reinhardt, "Meaningless Questions in Cosmology and Relativistic Astrophysics," *Zeitschrift für Naturforschung*, **31a**, 1976, 1271—1276.

[137] P. G. Bergmann, "Cosmology as a Science," *Foundations of Physics*, **1**, 1970, 22.