The Scientific Legacy of the 20th Century
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HOW TO BECOME SCIENCE?
THE CASE OF COSMOLOGY

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1. Before the Beginning of Relativistic Cosmology

When Aristotle was writing 'the least initial deviation from the truth is multiplied later a thousandfold',[1] he was not fully aware of how much it was true and how much it referred to himself. His errors in establishing details of phenomena indeed multiplied later a thousandfold, but consequences of his error in choosing the method for investigating nature multiplied even more.[2] It is often said that Aristotle's errors and his misguided method of investigating natural phenomena blocked scientific progress for many centuries. However, long periods of blundering are, in certain conditions, an unavoidable price of the final success. If this was true as far as natural sciences were concerned, it was even more so in the case of cosmology. It seemed to be a helpless case. From the present perspective it is hard to say what was more reasonable in this field: Aristotle's seemingly precise, but in fact most often purely verbal, analyses, or Plato's openly metaphorical narrations. Eudoxian crystalline spheres and Ptolemaic epicycles rendered a service to positional astronomy, but from the cosmological point of view, being contradictory with each other, immersed the science of the universe in a persistent crisis.

The birth of modern science in the 17th century only slightly improved the situation in this respect. The notion of the universe, inherited from the Ancients, extended from the sublunar area to the sphere of fixed stars, and this is why polemics around the Copernican system, that strictly speaking referred only to the planetary system, had in fact a cosmological aspect. But in this aspect, it introduced more misunderstanding than real progress. The true promise of future successes was the discovery of the universal character of the law of gravity, but for the time being it generated, when applied to cosmology, more problems than solutions. Newton was not exaggerating when he claimed that the supposition that there should be a particle so accurately placed in the middle of stars 'as to be always equally attracted on

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[1] *On the Heavens*, translated by J.L. Stocks, p. 271b.

[2] Aristotle, to be sure, was a great experimentalist of his time, especially in the field of life sciences, but controlled experiments played only a marginal role in his method.

all sides' is as difficult to implement as 'to make the sharpest needle stand upright on its point upon a looking glass'.[3] The problem of gravitational instability was one of the most difficult questions with which the physics of the universe had to cope.

Newton's conundrum with gravitational field instability, later known as the Seeliger paradox, led to some attempts at modifying the law of gravity, and quite unexpectedly surfaced in Einstein's first cosmological paper of 1917. In this paper, Einstein had to add to his equations the so-called cosmological constant to obtain a static model of the universe. It was a particularly malicious twist of history when some ten years later it turned out that the Einstein static model, in spite of this 'saving procedure', is in fact unstable.

The Seeliger paradox, in the 19th century, was paralleled by the optical Olbers paradox (in fact, this paradox was also known to Newton): if the infinitely extending universe is uniformly filled with stars (or galaxies, or galactic clusters, in the more modern version), the night sky should be as bright as the surface of the Sun, but this conclusion remains in sharp contrast with what can be seen with the naked eye.

In the second part of the 19th century there were strong reasons to believe that the universe as a totality cannot be made obedient to physical laws discovered in our local neighbourhood. Agnes Mary Clerke, the astronomer and historian of astronomy, was not an exception when, in 1890, she declared: 'With the infinite possibilities beyond [our Milky Way], science has no concern'.[4] Helge Kragh quotes an anonymous reviewer who in 1907 wrote: 'when there are no facts to be explained, no theory is required'.[5] In spite of these reservations, the universe is a challenge to the human mind. We prefer to create fancy hypotheses in order to tame the Unknown rather than to acknowledge our ignorance. Besides the 'cosmological skeptics', in the second half of the 19th century, there was a crowd of physicists, philosophers, amateurs, and sometimes also astronomers, who indulged their imagination and developed various cosmic scenarios.

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[3] Newton claimed even more: since there is an infinite number of stars in the universe, to make the system of stars stable '…this is as hard as to make, not one needle only, but an infinite number of them stand accurately poised upon their points'. Newton's Letter to Bentley, in: *Isaac Newton's Papers and Letters on Natural Philosophy*, ed. by I.B. Cohen, Harvard University Press, Cambridge, Mass., 1971, p. 292.

[4] After H. Kragh, *Matter and Spirit in the Universe*, Imperial College Press, London, 2004, p. 20.

[5] *Ibid.*

History of science, especially as it is done by working scientists, is often highly selective. It focuses on ideas from the past that later on evolved into commonly accepted theories or trends, but it forgets or overlooks those side-branches that blindly ended with no consequences. It is instructive to read in this respect the second chapter of the above-mentioned book by Kragh: how rich the spectrum of conceptions and views was, in the 19th century, that attracted the general public and engaged some scientists, but left no traces in our mainstream scientific cosmology. However, there were also ideas, considered at that time highly exotic, that now belong to the standard conceptual tool-kit of our theories.

2. Many Dimensions and Non-Euclidean Geometries

The discovery of non-Euclidean geometries by Gauss, Bolyai and Lobachevsky opened a vast field of possibilities. Riemann and Clifford speculated about their eventual applications to physics, and the idea soon captured general attention. A popular book by Edwin Abbot Abbot, first published in 1884, presenting the adventures of a two-dimensional Square (inhabitant of Flatland) in three-dimensional Spaceland, soon became a bestseller.

Ernst Mach in his influential *The Science of Mechanics* relegated the problem of multidimensional spaces to a long footnote at the end of the book.[6] He considered the discovery of non-Euclidean geometries as an important mathematical achievement, but 'we must not hold mathematicians responsible for the popular absurdities which their investigations have given rise to'. The space of our sensual experience is doubtlessly three-dimensional. 'If, now, it should be found that bodies vanish from this space, or new bodies get into it, the question might scientifically be discussed whether it would facilitate and promote our insight into things to conceive experiential space as part of a four-dimensional or multi-dimensional space. Yet in such a case, this fourth dimension would, none the less, remain a pure thing of thought, a mental fiction'. He then develops the topic of 'popular absurdities': 'The forth dimension was a very opportune discovery for the spiritualist and for theologians who were in the quandary about the location of hell'. When writing this ironic sentence, Mach probably had in mind the German astronomer Karl Friedrich Zöllner who became engaged in spiritualism and claimed that the fourth dimension well explains spiritualistic phenomena.

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[6] *The Science of Mechanics. A Critical and Historical Account of Its Development*, Open Court, La Salle, Illinois, 1974, pp. 589-591.

Besides this rather extravagant claim, Zöllner thought that non-Euclidean geometries were relevant for the study of the world as a whole.[7]

Zöllner was not alone to proclaim this idea. The first attempt to experimentally check the curvature of space should be attributed to Gauss himself who in his *Disquisitiones generales circa superficies curvas*, published in 1828, reported his experiment to survey a triangle formed by three peaks in the Herz mountains.[8] The result was of course negative. A more serious analysis of experimental possibilities in this respect was undertaken by Karl Schwarzschild. Before the Astronomische Gesellschaft in Heidelberg in 1900, he discussed four possible observational tests to detect space curvature: (1) the test from the minimal parallax of stars, (2) from the number of stars with different parallaxes, (3) from the possibility to see 'around the universe', and (4) from star count as a function of stellar magnitude. We should admire Schwarzschild's insight: having no help from a physical theory, such as later general relativity, he not only conceived four observational test, but also understood the necessity of taking into account various topological forms which could essentially modify the results.

As we can see, long before Einstein's special and general theories of relativity, some elements (such as multi-dimensionality and non-Euclidean geometries) that later on entered the very body of these theories, had already circulated among both scientists and amateurs. The point is, however, that Einstein, when time was ripe, did incorporate them into his way of thinking not by borrowing them from this circulation, but rather by distilling them from the logic of the evolution of physical problems.

Somewhere in the span of the 18th and 19th centuries, mainly due to the progress in astronomy, from rather fuzzy 'cosmological narratives' a core or a body of accepted views started to emerge that later became scientific cosmology. However, at that time these narratives were pushed to a fuzzy belt of speculations and hypotheses surrounding the core. When the science of the universe consolidates, some inhabitants of the belt assume more responsible forms and are absorbed by the core, some others are forgotten. The belt is important since it is an indispensable condition of progress. The situation becomes dangerous only when the subtle borderline between the core and the belt is regarded as non-existent.

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[7] More about Zöllner in: H. Kragh, *op. cit.*, pp. 24-26.

[8] See M. Heller, P. Flin, Z. Golda, K. Maslanka, M. Ostrowski, K. Rudnicki, T. Sierotowicz, 'Observational Cosmology. From Gauss to Sandage', *Acta Cosmologica* 16, 1989, 87-106.

3. The Beginning of Relativistic Cosmology

The birth of General Relativity was a real breakthrough, and that of relativistic cosmology a spectacular application of Einstein's theory to the biggest physical system conceivable. After years of struggle and several dramatic months of painful coda, Einstein, in November 1915, finally wrote down his gravitational field equations. They were his response to the critical situation in which Newton's theory of gravity was deeply immersed (crisis in any of the major physical theories always has an echo in other areas of science). Some people were aware of this and tried to remedy the situation by modifying Newton's law, but only Einstein, owing to his work in special relativity, was able to see the connection between gravity and the spacio-temporal framework of physics, and understood that Newton's gravity should not be amended but suitably replaced.

Einstein's answer to the crisis was a piece of art of enormous beauty. Even if the final act is a sort of illumination, it certainly did not come as *deus ex machina*. Einstein was led to it by a chain of almost deductive reasoning, based on clearly formulated questions of deep physical significance. This does not mean that sometimes the chain did not need enormous effort to make the reasoning transparent. To change his ideas into the body of a physical theory Einstein had to use completely new mathematical theories, known only to some experts in pure mathematics but foreign to the community of physicists. As a result, he obtained a set of ten partial differential equations, the richness of which he was only dimly aware of. It is true that in the compact tensorial form they look quite innocent, and when applied to various physical situations they usually simplify to a tractable mathematical form. Only after acquiring a certain familiarity with them, one can guess their abysmal richness from the fact that, when applied to different problems, they reveal unexpected layers of their mathematical structure. If you read in popular books that Einstein's equations present the gravitational field as the curvature of a four-dimensional space-time, it is only a shortcut of a vast empire of mutual interactions between non-Euclidean (pseudo-Riemannian, in modern parlance) geometries and various aspects of physical reality.

In 1917 Einstein produced his first cosmological paper. We already know the beginning of the cosmological constant story. This constant was, so to speak, enforced upon Einstein by his equations. Some ten years later, when it turned out that the universe is not static but expands, Einstein proclaimed the introduction of the cosmological constant 'the greatest blunder of his life'. But in proclaiming this, it was Einstein who was wrong, not his equations. From the mathematical point of view, the most general (and therefore the most beautiful) form of Einstein's equations is the one with the cosmological constant. And today there are strong reasons to believe that this constant has an important physical interpretation. From recent observations of the Ia type supernovae we know, with a good degree of credibility, that the universe not only expands, but also accelerates its expansion. And to obtain agreement between these observations and theoretical models one should employ the equations with the cosmological constant (see below).

This is a typical story. The history of relativistic astrophysics and relativistic cosmology from Einstein up to about the seventies of the previous century, consisted mainly in solving Einstein's equations, analyzing and interpreting the structures of these solutions, and then looking at the sky to verify what the equations had predicted (of course, it is a highly idealized picture). In this process, various groups of people were engaged, there were many disputes and erroneous interpretations, in some of them other departments of physics had to be involved. In this way, young relativistic cosmology slowly crystallized. The new field of research was created, still full of question marks but ready for further developments.

Einstein's paper of 1917 was definitely wrong. Its static world model does not represent the world we live in. But the paper was epoch making; it opened a new way in our thinking of the universe.

4. Domination of Philosophy

The next move belonged to the Dutch astronomer Willem de Sitter. The story is well known; I shall only very briefly sketch its main stages. Yet in 1917 de Sitter found another cosmological solution of Einstein's equations which represented a world devoid of matter (with vanishing matter density) and, as it turned out later, with expanding space, thus ruining Einstein's hope that the 'cosmological problem' would have a unique solution. In 1922 and 1924, Russian mathematician and meteorologist Alexander Alexandrovitch Friedman published two papers in which he presented two infinite classes of solutions with the positive and negative curvature of space, respectively. In 1927 Georges Lemaître, for the first time, compared theoretical predictions of one of the expanding cosmological models with the results of galactic red shift measurements, and found that there was no contradiction between them. All so far considered solutions satisfied the postulate of maximal spacial symmetry (isotropy and homogeneity of space).[9] Mathematical discussion of such models was undertaken by Howard Percy

[9] This postulate was called by Edward Arthur Milne the Cosmological Principle.

Robertson and Arthur G. Walker. Probably the first ever attempt to fill in the geometric scene, as given by Einstein's equations, with physical processes reconstructing the history of the universe, belonged to Lemaître. It was called by him the Primeval Atom Hypothesis.

In the meantime extra-galactic astronomy gradually made a significant progress. After the discovery, in 1929, by Edwin Hubble of what is now known under the name of Hubble's Law (linear dependence of red shifts on distance for distant galaxies), the effect of the 'expansion of the universe' was reasonably well established, but the results of measurements were not enough to select a model, or a class of models, that would best fit the data. Another information important for cosmology, which should constitute its observational input, the uniform distribution of galaxies, was regarded as a simplifying postulate rather than the result of observation.

It goes without saying that it is a very sketchy picture of the situation. We should notice that cosmology at that time was regarded as a true science only by a very few, the main objections being: the lack of reliable experimental data, the huge degree of extrapolation and, quite often, the lack of confidence towards Einstein's theory of gravitation as a fully-fledged physical theory. No wonder that in such a situation philosophical prejudices played a greater role than is usually the case in the sciences. Mutual influences went in both directions: from philosophy to cosmological models, and from works in cosmology to philosophical views. For instance, philosophical views on the creation of the universe or its eternity influenced preferences of cosmological models with the initial singularity or with cyclic histories. On the other hand, since the majority of early works concerned spatially closed world models, the philosophical idea was favoured that space should be closed, otherwise it would not be cognizable to the human mind. The latter view is encapsulated in bishop Barnes' statement at the meeting of the British Association for the Advancement of Science in 1931, that 'infinite space is simply a scandal for human thought'.[10]

After the Second World War, cosmology resumed its progress more or less in the same style as before the war, but its theoretical environment slowly started to change. General relativity gradually became a fully acknowledged physical theory, more theoretical works related to this theory were accumulating, and its role in physics was increasingly important. These changes were not directly related to cosmology but, some two decades later,

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[10] 'The Evolution of the Universe', *Supplement to Nature*, n. 3234, 1931, 704-722. This is a report of the discussion held at the British Association.

these processes significantly contributed to an acceleration in cosmological research. For the time being, cosmology continued to be dominated by philosophical speculations and polemics. One of the hottest topics was the problem of the beginning of the universe. Lemaître, after an early attempt to avoid this problem,[11] tried to incorporate the beginning ('natural beginning' as he called it) into the physical scenario. This aroused a strong reaction from some scientists who suspected in this move a hidden religious propaganda. In 1948, Herman Bondi, Thomas Gold and Fred Hoyle published their steady-state cosmology.[12] The clear motivation was to counteract the influence of the Big Bang theory.[13]

The universe is expanding. In the face of accumulating data this cannot be denied. The only way to save its eternity (no beginning) is to assume that matter is being created out of nothing to maintain world's constant density (this postulate was called the Perfect Cosmological Principle). It can be calculated that the creation rate necessary to obtain this goal is undetectable on the local scale. Initially, steady state cosmology met some resistance but later on, owing mainly to Hoyle's propaganda activity, discussions between steady state and Big Bang theories dominated the cosmological scene. Lemaître, highly disappointed, lost his interest in cosmology and turned to numerical computation.

There is no need to focus on this story; it was extensively studied by Helge Kragh, and the interested reader should be referred to his book.[14] It is a common conviction that it was the discovery of the cosmic microwave background (CMB) radiation that killed the steady state theory, although Kragh's study shows that at the time of this discovery the steady state theory was already practically dead.

5. Standard Model of the Universe

The great breakthrough in cosmology occurred in the sixties of the previous century. Although the existence of CMB was predicted already in

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[11] In his work of 1927 he chose a model (later called Eddington-Lemaître world model) with no singularity to compare it with observational data.

[12] In Bondi and Gold's version the idea was based on speculative assumptions; Hoyle based his version on an unorthodox interpretation of de Sitter's solution to Einstein's equations.

[13] Somewhat later Hoyle used, for the first time, the term Big Bang as an ironic nickname of Lemaître's cosmology.

[14] *Cosmology and Controversy. The Historical Development of Two Theories of the Universe*, Princeton University Press, Princeton, 1996.

1948 by George Gamow and his coworkers and, quite independently of their work, there were some hints of its presence based on observed excitations of CN particles in clouds of interstellar space, nobody was able to appreciate the impact the CMB discovery was to make on cosmology. Its main merit was not so much that it contributed to eliminate sterile discussions around steady state cosmology but, first of all, that it has provided means to obtain access to the physics of the early universe. The discovery of quasars, almost at the same time, trigged interest in extra-galactic astronomy. Progress in radio astronomy and in optical astronomy was providing richer and richer data concerning the large-scale distribution of matter.

An insight into physical processes in the early universe gave momentum to the theory of nucleosynthesis, also initiated by Gamow and his team. The works by Margaret Burbidge, Geoffrey Burbidge, William Fowler and Fred Hoyle (initially done in the framework of the steady state cosmology) provided the part of the nucleogenesis theory missing in Gamov *et al.*'s works (formation of heavier elements in the interiors of massive stars). The observed abundances of chemical elements in the universe well agreed with theoretical models. Especially, the determination of the primordial deuterium abundance turned out to be a very sensitive cosmological test (it led to tight constraints for the baryon density a few minutes after the Big Bang).

All these achievements (and many others as well) created a basis for establishing the hot model of the universe (as it was then called) – a reconstruction of physical processes from the proverbial 'first three minutes' after the Big Bang, through the radiation era, and the origin of galaxies and their clusters to the present cosmic era. We should acknowledge the great contribution to this scenario of the Moscow school led by Yakov Borisovich Zel'dovich. With the incoming of observational data and the progress in theoretical works, the model of the hot universe slowly changed into what is now called the standard model of the universe – the commonly accepted scenario of the evolution of the universe. Of course, there were some opponents who tried to defend 'alternative cosmologies', but their works had only a marginal influence on mainstream cosmology.

When progress is made, details are seen more sharply which, in turn, allows one to see problems and difficulties previously invisible or dimly visible. Several such problems were identified in the otherwise very successful standard model. Let us enumerate some of them:

The horizon problem. The anisotropy of CMB is now known to be less than 10^{-4}. How to explain this degree of uniformity at two points in the sky that are separated by the causal horizon (the distance between such points is greater than that which light can cover since the initial singularity)?

The flatness problem. How to explain the fact that the parameter $\Omega=\rho/\rho_{cr}$ is very close to unity? Here ρ is the present density of matter, and ρ_{cr} is the density of matter characteristic for the flat cosmological model. It should be noticed that $\Omega=1$ is an 'unstable' value in the standard model.

The monopole problem. How to explain the fact that the standard model predicts an overproduction of magnetic monopoles, and they are not observed in the present universe?

The origin of structures problem. How to explain the generation of density fluctuations in the early universe (they are indispensable to form stars, galaxies, cluster of galaxies…)?

In 1981 Alan Guth proposed the first inflationary model (now there is almost infinite number of them). Enormously accelerated expansion (by the factor greater than 10^{30} in less than 10^{-32} sec.) blows up an inside-the-horizon part of the universe to a size greater than the present observable universe. This hypothesis almost automatically solves all the above enumerated problems,[15] and this is certainly its great merit, but the inflationary scenario also has its great problems. As nicely summarized by Andrew Taylor: 'There is no fundamental physics underlying inflationary models, unlike say the Big-Bang model which is based on General Relativity. Inflation takes many of its ideas from 'quantum field theory', but the fields it uses are not directly related to the known fields of nature. If it turns out to be true, inflation implies there is a wealth of physics beyond what we currently understand'.[16]

In the last decades of the 20th century we could observe two great streams in the study of the universe: the stream of audacious hypotheses and models aiming at solving all cosmological conundrums, and the stream of 'very responsible' investigations based on increasingly rich influx of observational data. The emerging image of the cosmic evolution is composed out of the network of very precise (in numerical sense) details with interspersed vast patches of unknown large-scale features. And an active interaction of both these streams is a promise of the future progress. Let us first focus on what is sometimes called the precision cosmology.

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[15] See e.g., S.K. Blau, A.H. Guth, 'Inflationary Cosmology', in: *Three Hundred Years of Gravitation*, eds.: S.W. Hawking, W. Israel, Cambridge University Press, Cambridge, 1987, pp. 524-603.

[16] A Taylor, 'The Dark Universe', in: *On Space and Time*, ed. by Sh. Majid, Cambridge University Press, Cambridge 2008, pp. 1-55, quotation from pp. 16-17.

6. Precision Cosmology

New generations of surface telescopes, Hubble space telescope, technologically advanced radio observatories, and cosmic missions, especially those of COBE, WMAP and Planck satellites, are providing an avalanche of data of great cosmological interest. Owing to these new technologies the wavelength range is covered spanning from radio and optical waves, through microwave to X-rays and gamma rays. Let us enumerate a few fields in which progress is tremendous.

First, *CMB measurements*. Owing to CMB anisotropies on angular scales between 10º (Planck satellite is expected to go with the measurement precision dawn up to 0.1º) and 100º it is possible to determine, with great precision, the amplitude of mass fluctuations at the epoch before nonlinear structures are formed. The power spectrum of temperature fluctuations of CMB carries a lot of information about the early universe. The peaks observed in the CMB power spectrum are due to baryon-photon oscillations driven by the gravitational field. Their precise measurements help establishing (with smaller and smaller errors) important parameters characterizing the cosmological model (see below), and provide information concerning initial conditions for the structure formation.

Second, *mapping three-dimensional large-scale distribution of galaxies*. Two-degree-Field Galaxy Redshift Survey (2dF or 2dFGRS) was conducted by the Anglo-Australian Observatory between 1977 and 2002. The spectra of 245,591 objects were measured, including 232,155 galaxies, 12,311 stars and 125 quasars. Another, even larger program of this kind is the Sloan Digital Sky Survey (SDSS). In over eight years of its operation it has obtained deep, multi-colour images covering more than a quarter of the sky. Consequently, it was possible to create three-dimensional maps containing more than 930,000 galaxies and more than 120,000 quasars. Such programs are not only important for themselves but they also give, in combination with CMB measurements, two ‘photographs’ of the universe: one 300,000 years after the Big bang, and another at the present epoch.

Third, *gravitational lensing* which allows us to measure directly overdensities of dark matter at moderate red shifts. In a typical one square degree piece of the sky there are million of galaxies, and dark matter density perturbations systematically disturb images of these background galaxies along the line of sight. This turns out to be a very effective method of observing what is not observable otherwise. Numerical simulations are a bridge between these observations and theoretical models.

Fourth, *measuring cosmological parameters* (by using the above and other methods). They are extremely important for determining this cosmological model (or this subclass of cosmological models) that best fit observational data. Here are some recent results:[17]

Hubble parameter $h = 0.72 \pm 0.03$ in units of 100 Km s^{-1} Mpc^{-1},
total matter density $\Omega h^2 = 0.133 \pm 0.006$,
baryon density $\Omega_b h^2 = 0.0227 \pm 0.0006$,
cosmological constant $\Omega_\Lambda = 0.74 \pm 0.03$,
radiation density $\Omega_r h^2 = 2.47 \times 10^{-5}$,
density perturbation amplitude $= 2.41 \pm 0.11) \times 10^{-9}$.

From the above results quite a detailed picture of the large-scale universe emerges; its age being equal to 13.73 billion years (with an uncertainty of 120 million years), and its space flat with only a 2% margin of error. The evolution of chemical elements and the evolution of structures are also well understood. The standard cosmological model is no longer reduced to the 'geometry of the Universe', i.e. to solving Einstein's equations and trying to select a solution (or a family of solutions) that best fits observational data (as it was in the first half of the 20th century), but becomes a true 'physics of the universe'. In fact, there are almost all physical theories that participate in reconstructing processes involved in shaping the structure and evolution of the universe. One often speaks about cosmology as an effective physical theory, i.e., as the result of cooperation of various physical theories or models that contribute effectively to a coherent image of the world.

5. Unsolved Problems in Cosmology

There are two sources of 'learned ignorance' in cosmology. One is the fact that the more details we know, the more penetrating questions we ask. The second follows from the very nature of cosmology – the science of totality. Facing totality it is hard not to ask questions that cannot be kept within the constraints of the empirical method. Let us start with those of a more technical character. As we shall see, they 'smoothly' go on to more metaphysical ones.

1. *The cosmological constant problem.* The essence of the problem consists in the fact that if we agree that the cosmological constant is related to the energy

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[17] They are taken from: O. Lahav, 'The Cosmological Parameters', arXiv:1002.3488 [astro-ph.CO], 18 Feb. 2010. Interesting review: W.L. Freedman, 'Determination of Cosmological Parameters' (Invited review given at the Nobel Symposium, 'Particle Physics and the Universe'), Haga Slott, Sweden, August, 1998, *Physica Scripta*, T85, 2000, 37-46.

of quantum vacuum, then the current quantum field theories predict its value to be bigger by a factor of 10^{120} than the value implied by cosmological observations. This can be regarded as 'the worst theoretical prediction in the history of physics'.[18] So far there is no convincing explanation of this discrepancy. However, quite popular is the proposal made by Steven Weinberg to explain it by appealing to the anthropic principle.[19] If we suppose that vacuum energy assumes different values in different domains of the universe, then observers (such as ourselves) could only live in the domains in which the vacuum energy is similar to what we actually observe (such domain would be very rare). Essentially, large negative values of vacuum energy would imply a closed universe with too short a time for life to emerge; and large positive values would prevent galaxies and stars to form, which seem necessary for the evolution of life. A modification of Weinberg's proposal is to consider various 'parallel universes' instead of various domains of the same universe.

2. *The matter-antimatter asymmetry problem*. In the present universe we observe the strong asymmetry between baryonic and antibaryonic matter. Neither the standard particle model nor relativistic cosmology give us any explanation of this asymmetry. If the Big Bang produced equal amounts of particles and antiparticles (which seems to be a natural assumption), the universe would by now be a sea of photons (as the result of annihilation). How to explain that the universe is composed of matter rather than of only photons or antimatter? A natural reaction to this question is to look for the violation of the CP symmetry in the foundations of quantum field theories, but so far there is neither theoretical nor experimental evidence supporting this solution. Another explanation is again based on an anthropic reasoning and tries to restore the full matter-antimatter symmetry either on the level of various domains of our universe or on the level of the multiverse (a family of parallel universes).

3. *The dark matter problem*. The existence of a dark matter is deduced from the discrepancy between measurements of the mass of luminous objects (stars, galaxies, clusters of galaxies,…) and estimates made with the help of dynamical theories. According to present cosmological data, dark matter is responsible for 23% of the total mass-energy density of the observable universe, whereas ordinary matter only for 4.6%. The remainder is due to dark

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[18] M.P. Hobson, G.P. Efstathiou, A.N. Lasenby, *General Relativity: An Introduction for Physicists*, Cambridge University Press, Cambridge, 2007, p. 187.

[19] S. Weinberg, 'Anthropic Bound on the Cosmological Constant', *Phys. Rev. Lett.* 59 (22), 1987, 2607-2610.

energy (see below). Dark matter (at that time called 'missing mass') was suggested, as early as in the thirties of the 20th century, by Fritz Zwicky. It plays an important role in current theories and models of structure formation in the universe and explanations of anisotropies observed in CMB. The very nature of dark matter and its interaction with electromagnetic radiation remain open questions.

4. *The dark energy problem*. Dark energy is a hypothetical form of energy responsible for the increase in the expansion rate of the universe inferred from the recent observations of supernovae of Ia type. It is supposed to account for 74% of the total mass-energy of the universe. The most probable form of dark energy is the cosmological constant corresponding to a constant energy density filling space in a homogeneous manner. Another possibility is provided by scalar fields, sometimes called quintessence; their energy density can vary in space and time. Determining the equation of state for dark energy (i.e., a relationship between energy density, pressure and vacuum energy density) is one of the biggest challenges of today's cosmology. The so-called Lambda CDM model, based on a FLRW solution to Einstein's equations with the cosmological constant, gives very good agreement with current observational data. The cosmological constant (Lambda) in this model is interpreted as responsible for dark energy.

5. *The horizon problem* (see above, section 5). The essence of the problem consists in the fact that even distant places in the universe exhibit the same (up to a high precision) characteristics, e.g., the same CMB temperature, in spite of the fact that they have never been in the causal contact (since the Big Bang). Some 300,000 years after the Big Bang photons decoupled from the other forms of matter. At that time the volume of a 'causally connected' region was about 900,000 light years across, whereas today the CMB temperature is the same over the entire sky, the volume of which is 10^{88} times larger. The most common explanation of this huge discrepancy appeals to the inflation in the very early history of the universe, which blew up a tiny causally connected region to the size containing the present observable universe. It was one of the reasons of the origin of the inflationary scenario.

6. *The inflation problem*. Inflationary models not only solve the horizon problem, but also some other problems of traditional cosmology (the matter-antimatter problem, the flatness problem, the horizon problem), but they themselves require rather special initial conditions, and still there is no decisive empirical evidence for the existence of inflation in the very early period of cosmic evolution. There are so many scenarios of inflation that – as it is sometimes claimed – at least one of them must fit empirical data. The truth is that inflation, when combined with the Cold Dark Matter (CDM)

scenario (which is today the most favoured one) predicts Gaussian perturbations, independent of scale, in the early universe. The model is characterized by at least ten parameters. This indeed creates serious problems as far as empirical testing is concerned, but with the abundance of high precision data, which continue to come, this also fosters hopes for solving riddles of the early universe. As noticed by George Ellis, 'It is this explanatory power that makes it [the inflationary scenario] so acceptable for physicists, even though the underlying physics is neither well-defined nor tested, and its major large-scale observational predictions are untestable'.[20]

7. The quantum cosmology problem. This is a subproblem of a major problem important for the entire physics, namely of the quantum gravity problem. The physics of the microworld is dominated by quantum mechanics and quantum field theories, whereas the physics of the world on the large scale (including cosmology) is dominated by general relativity. There is common agreement that on the fundamental level these two physical theories should be unified into one theory, called quantum gravity theory. In the very early stages of cosmic evolution, extremely strong gravitational fields had to reveal its quantum nature, and standard cosmology should be replaced by quantum cosmology. The most developed approaches to quantum gravity are superstring theory (and its newer incarnation, M-theory) and loop quantum gravity. The former attempts to unify quantum physics, gravitational physics and the physics of other fundamental interactions (electromagnetism, and strong and weak nuclear forces), whereas the latter simply quantizes the gravitational field, putting aside other interactions. Other attempts include: supergravity, causal dynamical triangulation, Regge calculus, twistor theory, causal sets, and approaches based on noncommutative geometry and quantum groups.

7. *The multiverse problem*. As we have seen, the concept of multiverse was invoked as a possible explanation for various problems. The concept of the multiverse itself changes depending on the problem that it is supposed to solve. The main concern related to the multiverse idea is whether it can be regarded as belonging to the realm of science. This concern comes from the fact that the concept itself is very fuzzy and has hardly any observational consequences. George Ellis justly remarks: 'Choices are needed here. In geometrical terms, will it [the multiverse] include only Robertson-Walker models, or more general ones (e.g. Bianchi models, or models without symmetries)? In gravitational terms, will it include only General Relativity, or also brane

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[20] G.F.R. Ellis, 'Issues in Philosophy of Cosmology', arXiv:astro-ph/0602280 v2.

theories, models with varying *G*, loop quantum gravity models, string theory models with their associated possibility 'landscapes', and models based on the wave function of the universe concept? Will it allow only standard physics but with varying constants, or a much wider spectrum of physical possibilities, e.g. universes without quantum theory, some with five fundamental forces instead of four, and others with Newtonian gravity? Defining the possibility space means making some kinds of assumptions about physics and geometry that will then apply across the whole family of models considered possible in the multiverse, and excluding all other possibilities'.[21]

As far as the empirical testability is concerned, the problem arises of whether we may trade testability for the explanatory power of the multiverse idea. But the explanatory power of this idea is still highly debatable.

8. Summary and Perspectives

The history of cosmology in the last one hundred and fifty years or so is a beautiful example of how wild speculations and unverifiable hypotheses could change into reliable science. Before that time the only link of cosmology with reality was local physics. One thing was known for sure: that the universe at large must be such as to allow for what we know about here and now. An extrapolation from here and now was the main strategy of cosmological speculations.

There is a certain regularity in the history of science. In every epoch a hard core of scientific theories is surrounded by a vast band of speculations that are controlled mostly by common sense intuitions and philosophical prejudices. Some of these speculations may inspire fruitful ideas and, after suitable transmutations, become elements of genuine science, but the majority of them will turn out to be alleys leading to nowhere and will be forgotten or quoted in footnotes of the history of science.

In the last decades of the 19th century something started to happen in the bordering zone between the hard core of physics and the surrounding belt of cosmological speculations. Advances in astronomy and pressing questions from the Newtonian gravity put the case of cosmology on the market. Various speculations generated by the discovery of non-Euclidean geometries and adding more space dimensions to the traditional three turned the attention of some physicists and philosophers to the problem of the spatial arena for physical processes. The latter concept soon evolved, in the works of Einstein and Minkowski, into the concept of space-time, which in itself

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[21] *Ibid.*

had cosmological connotations. The birth of Einstein's general theory of relativity created a new theoretical context for thinking about the universe. Some concepts so far dwelling in the belt surrounding science started to infiltrate the domains of physical theories. The process was slow and painful. Cosmology already had a consolidating conceptual basis, but was still dominated by philosophical presuppositions and prejudices. In the beginning of this process the observational basis of cosmology was rather fragile (only galactic red shifts with an uncertain Doppler interpretation and very rough data concerning the uniform distribution of matter), but as this basis gradually strengthened, some philosophical assumptions changed into working, observationally motivated models.

After the breakthrough of the sixties and the influx of observational data (trigged mainly by the discovery of CMB), the status of cosmology as a scientific discipline was established, and the standard model of the universe quickly started to emerge. This process was accompanied by a gradual coalescence of cosmological theories and models with other branches of physics. The fact that cosmological theories and models have to make use of physical phenomena studied in other departments of physical sciences is rather obvious, but the fact that also other physical theories (such as, for example, the theory of elementary particles) found this useful to conduct their investigation in a purposefully chosen cosmological context, was certainly a sign of the acceptance of cosmology into the family of empirical sciences.

This process substantially strengthened when, in the last decades, 'precision cosmology' entered the scene. Today, several programs of key significance for physics and astronomy could not even be imagined without the 'cosmological background'. It is enough to mention the program of unification of all fundamental forces and the theory of the origin and evolution of complex structures. Cosmology itself has become what is now called effective physical theory, i.e., the field of the effective cooperation of many physical disciplines.

The result is impressive: a very detailed, although still incomplete, scenario of cosmic evolution. Major problems plaguing cosmology (which are enumerated in sections 5 and 7) testify to this incompleteness. However, these problems could also be regarded as achievements of cosmology. Yet a few decades ago some of them could not even be suspected, and to replace an invisible hole with an open question is certainly a step in the right direction.

Since the majority of these problems are difficult and some of them balance on the verge of the scientific method, they easily give rise to new layers of the speculative belt surrounding current research in cosmology. Do some newer ideas inhabiting this belt have a chance of becoming full-fledged cosmological models some day? Let us compare the present situation with that from before the beginning of relativistic cosmology. At that time there were many ideas, which had to be regarded as inhabiting the belt, that by now are completely forgotten. For instance, the hypothesis invented and propagated by the Scottish physicist William Rankine who claimed that when radiant heat reaches a boundary of the interstellar medium (beyond which there is only empty space), it is reflected and could concentrate again, in this way averting the otherwise unavoidable thermal death of the universe.[22] On the other hand, some other bold ideas had matured and were fully incorporated into the body of science. Typical examples are vague speculations around non-Euclidean geometries and multidimensional spaces which have changed into indispensable tools of physical theories.

Something similar is to be expected as far as present speculations about 'unsolved problems in cosmology' are concerned. I think that such problems as the cosmological constant problem, dark matter and dark energy problems will sooner or later be solved, and their solutions will contribute to establishing new reliable cosmological scenarios. It could also be that some 'unsolved problems' will simply be liquidated by new more precise measurements, as it happened in the fifties of the last century with the age of the universe problem. The age of the universe as computed from the Hubble law was at that time shorter than the age of some rocks on Earth, meteorites and certain stellar systems. This was one of the main difficulties in relativistic cosmology in first decades of its existence. In 1955 Walter Baade discovered a systematic error in determining distances to galaxies, and when that error had been corrected the problem disappeared.

The fate of some other speculations is more debatable. I have in mind the whole collection of speculations related to the multiverse idea. I think two factors should be taken into account. First, as remarked in section 7, the multiverse concept is very vague, and in order to be scientifically productive it must be suitably narrowed (this in fact happens in the works of many authors). Some more precisely defined 'parallel universes' possibly have a chance to fulfil a positive role (at least a heuristic one) in cosmology,[23] provided that – and it is the second factor – some methodological standards

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[22] See, H. Kragh, *Matter and Spirit in the Universe*, p. 47. Chapters 1 and 2 give more examples of this kind.

[23] George Ellis in his paper 'Multiverses: Description, Uniqueness and Testing' (in: *Universe or Multiverse*, ed. by B. Carr, Cambridge University Press, Cambridge 2007, pp. 387-409) discusses possible restrictions that could render the multiverse concept scientifically more acceptable.

in cosmology and in fundamental physics will somehow be relaxed. The present paradigm in cosmology is that of physics, and physical methodology is based on empirical testability. If we stick to this paradigm, the multiverse methodology has negligible chances. If we admit that, in some cases, an explanatory power (in a non-empirical sense or in a relaxed empirical sense) could supplement accepted strategies in the physical sciences then some versions of the multiverse strategy could possibly be viewed more favourably in the domain of science. This is a philosophical option, and there are signs that such an option is indeed slowly gaining acceptance. This is understandable in the sense that when theoretical curiosity reaches the limits of experimental possibilities, there is no other way round than to look for help in bold speculations. Although some people claim that when this happens, science starts to decline.