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Contemporary History of Cosmology and the Controversy over the Multiverse

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Summary

Cosmology has always been different from other areas of the natural sciences. Although an observationally supported standard model of the universe emerged in the 1960s, more speculative models and conceptions continued to attract attention. During the last decade, ideas of multiple universes (the 'multiverse') based on anthropic reasoning have become very popular among cosmologists and theoretical physicists. This had led to a major debate within the scientific community of the epistemic standards of modern cosmology. Is the multiverse a scientific hypothesis, or is it rather a philosophical speculation disguised as science? This paper offers a review of the recent and still ongoing controversy concerning the multiverse, emphasizing its foundational nature and relation to philosophical issues. It also compares the multiverse controversy to some earlier episodes in the history of twentieth-century cosmology when particular theories and approaches came under attack for betraying the ideals of proper science.

Contents

We may conclude that there is not now a plurality of worlds, nor have there been, nor could there be. The world is one, solitary and complete.—Aristotle, *De caelo* (*c.*340 BC)

It may be also allow'd that God is able to Create Particles and Matter of several Sizes and Figures, and in several Proportions to Space, and perhaps of different Densities and Forces, and thereby to vary the Laws of Nature, and make Worlds of several sorts in several Parts of the Universe.—Newton, *Opticks* (1730)

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1. Introduction

'Scientific theories particularly those metaphysical and mystical theories which touch on the universe at large or the nature of life, which had been laughed out of court in the eighteenth and nineteenth centuries, are attempting to win their way back in scientific acceptance'. This quotation is not of recent origin, but appears in John Desmond Bernal's *The Social Function of Science*, a pioneering work on the political and sociological aspects of science published in 1939.[1] Yet the quotation might as well—and with even more justification—have referred to the situation in parts of physics and cosmology in the early twenty-first century. It is a widespread feeling in the community of theoretical physics that fundamental physics, in particular as related to cosmology and theories of quantum gravity, may be on its way to undergo a major epistemic shift. As witnessed by such new branches as multiverse cosmology, astrobiology, string-based pre-big bang cosmology, and 'eschatological physics', scientific speculations are highly regarded by many physicists and seen in a different, more positive light than earlier.[2] There are clear indications that traditional standards of physics are increasingly being questioned and sought replaced by alternative non-empirical criteria of evaluation.

The claims of an epistemic shift leading to a 'new paradigm' are of great philosophical and historical interest as they are truly foundational: they offer nothing less than a new answer to the question of what constitutes legitimate science, or at least legitimate physical science. The aim of this paper is not to judge whether recent claims of epistemic shifts in cosmology are justified or not, but to review the situation from a historical and partly philosophical perspective. Obviously, my concerns as a historian of science do not necessarily coincide with those of practising physicists and cosmologists.

Among the branches of 'extreme physics' here referred to, string theory is probably the field that has attracted most attention, both among physicists and philosophers.[3] Is the family of string theories (amalgamated in so-called M theory) empirically testable? By what standards do string theorists justify progress in their field? Interesting as these questions are, in this paper I shall not consider string theory but the class of cosmological theories which postulate the existence of many universes, often referred to as the multiverse. (Other names appear in the literature, such as 'megaverse', 'pluriverse', and 'parallel universes'.) Multiverse theories have recently become very popular and are taken seriously by many leading cosmologists, while other physicists and cosmologists view them as basically non-scientific. During

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[1] John D. Bernal, *The Social Function of Science* (London, 1939), 3. Bernal apparently had in mind scientists such as J. Jeans, A.S. Eddington, A.N. Whitehead and J.S. Haldane.

[2] Physical eschatology denotes attempts to forecast the far future state of the universe on the basis of existing scientific knowledge. For a bibliographic overview, see Milan M. Ćirković, 'Resource Letter: Pes-1: Physical Eschatology', *American Journal of Physics*, 71 (2003), 122–33. In so far as it takes into account the possibility of life, as it often does, physical eschatology links to speculative astrobiology. An example is N.E.H. Prince, 'Simulated Worlds, Physical Eschatology, the Finite Nature Hypothesis and the Final Anthropic Principle', *International Journal of Astrobiology*, 4 (2005), 203–26.

[3] There is no good historical study of string theory, ranging from its birth in the late 1960s to the present. An interesting account of the development until the early 1990s is provided in Peter Galison, 'Theory Bound and Unbound: Superstrings and Experiments', in *Laws of Nature: Philosophical, Scientific and Historical Dimensions*, edited by Friedel Weinert (Berlin, 1995), 369–407. On the philosophical aspects, see Reiner Hedrich, 'The Internal and External Problems of String Theory: A Philosophical View', *Journal of General Philosophy of Science*, 38 (2007), 261–78 and Richard Dawid, 'On the Conflicting Assessment of the Current Status of String Theory', http://philsci-archive.pitt.edu/ (2008).

the last few years a lively debate has taken place concerning the scientific nature of the multiverse, a debate which has provoked some participants to suggest quite radical departures from the traditional notion of science as a way of knowing that depends crucially on empirical evidence. According to some multiverse advocates, the epistemic shift under way includes a shift in the relationship between science and philosophy. 'The borderline between physics and philosophy has shifted quite dramatically in the last century', says US physicist Max Tegmark. 'I think it's quite clear that parallel universes are now absorbed by that moving boundary. It's included within physics rather than metaphysics'.[4] Critics of the multiverse disagree.

The paper starts with a look back in time, to some earlier episodes in the history of modern cosmology when the scientific nature of theories about the universe was questioned. The episodes are not chosen because they fit into the historical trajectory of multiverse models, but because they are methodologically comparable with the modern case. After providing a brief historical survey of the concept of the multiverse in twentieth-century cosmology, I proceed to discuss the basic ideas of the modern versions of the multiverse. My focus is in particular on notions such as testability, falsifiability, and predictions, concepts which are at the very heart of the current discussion. A central question in the debate relates to the classical demarcation criteria between science and non-science. Are the cosmologists obliged to follow the rules of the philosophers, or are they free to decide for themselves what counts as science and what does not? This and other issues of philosophical relevance are brought up in the final section.

2. Some historical precedents

During the period from about 1930 to 1960, cosmology was in a state of flux and characterized by a great deal of uncertainty with regard to foundational issues. Although relativistic cosmology was the favoured theoretical framework, there was no shared paradigm of what constituted the methods and aims of the science of the universe. Indeed, it was a matter of dispute whether such a science existed at all. Among the rival conceptions, Edward Arthur Milne's 'kinematic relativity' programme was influential during the 1930s and 1940s, and the steady-state theory of Fred Hoyle, Hermann Bondi and Thomas Gold was similarly important during the 1950s. None of these alternatives built on Einstein's theory of general relativity.

Although the ideas of Milne and Arthur Stanley Eddington differed in many respects, they had in common that they were ambitious attempts to reconstruct cosmological physics and found it on general principles of an a priori nature rather than observations. Resting on simple kinematic concepts such as distance and time, Milne's system was a peculiar mixture of positivism, conventionalism, and rationalism.[5] As he saw it, observational knowledge was of no great significance in our understanding of the universe:

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[4] Quoted in Charles Seife, 'Physics Enters the Twilight Zone', *Science*, 305 (2004), 464–65, p. 465.

[5] For Milne's cosmology and its associated methodology, see e.g. George Gale, 'Cosmology: Methodological Debates in the 1930s and 1940s', http://plato.stanford.edu/entries/cosmology-30s/ (2002) and Thomas Lepeltier, 'Edward Milne's Influence on Modern Cosmology', *Annals of Science*, 63 (2006), 471–81.

> The philosopher may take comfort from the fact that, in spite of the much vaunted sway and dominance of pure observation and experiment in ordinary physics, world-physics propounds questions of an objective, non-metaphysical character which cannot be answered by observation but must be answered, if at all, by pure reason; natural philosophy is something bigger than the totality of conceivable observations.[6]

Milne admitted that predictive power was essential to any scientific theory, but he also argued that an acceptable theory must be philosophically satisfying and that this was no less important. Incidentally, his cosmological model featured a uniformly expanding universe in flat space governed by the cosmological principle, which was a key concept in Milne's cosmology (the principle states that the universe is uniform—homogeneous and isotropic—on a very large scale). His universe, containing an infinite number of separate galactic regions, was therefore a kind of multiverse.

Although Eddington's cosmological views were fairly orthodox and conformed with the standards of general relativity, he was convinced that the key to knowledge about nature was to be found in epistemic rather than empirical considerations. The laws of nature were essentially the constructions of the human mind and therefore corresponded to a priori knowledge. He proudly declared that his fundamental theory of electrons and protons did not need to appeal to experimental tests: 'It should be possible to judge whether the mathematical treatment and solutions are correct, without turning up the answer in the book of nature. My task is to show that our theoretical resources are sufficient and our methods powerful enough to calculate the constants [of nature] exactly—so that the observational test will be the same kind of perfunctory verification that we apply sometimes to theorems in geometry'.[7]

The cosmophysical theories of Milne and Eddington, as well as the cosmological theory proposed by Paul Dirac in 1937, gave rise to a heated controversy among British physicists and astronomers.[8] The astrophysicist and philosopher of science Herbert Dingle led the crusade against the 'modern Aristotelians' whom he accused of betraying the inductive-empirical method of science. He was particularly worried about Milne's foundation of cosmology in the cosmological principle and even more so about Dirac's large number hypothesis, which he saw as nothing but 'a pseudo-science of invertebrate cosmythology'.[9] According to Dingle and his allies, principles of an a priori nature could have no legitimate place in science; if a cosmological theory built upon such 'chimeras', it was by definition pseudo-scientific. Although Dingle's view was rather extreme, and his language even more so, he was far from the only one who objected to the rationalistic tendencies in fundamental physics.

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[6] Edward A. Milne, *Relativity, Gravitation and World-Structure* (Oxford, 1935), 266.

[7] Arthur S. Eddington, *Relativity Theory of Protons and Electrons* (Cambridge, 1936), 3. Eddington's attempt to establish a new paradigm of physics is notoriously difficult to comprehend. For an attempt to reconstruct his line of thought, see Clive W. Kilmister, *Eddington's Search for a Fundamental Theory: A Key to the Universe* (Cambridge, 1994).

[8] On this debate, see Helge Kragh, 'Cosmo-Physics in the Thirties: Towards a History of Dirac Cosmology', *Historical Studies in the Physical Sciences*, 13 (1982), 69–108 and G. Gale and Niall Shanks, 'Methodology and the Birth of Modern Cosmological Inquiry', *Studies in History and Philosophy of Modern Physics*, 27 (1996), 279–96.

[9] Herbert Dingle, 'Modern Aristotelianism', *Nature*, 139 (1937), 784–86, p. 785. The large number hypothesis states that the numerical regularities exhibited by very large dimensionless numbers (such as 10^{40} and 10^{80}) constructed from the constants of nature express significant physical relations. Based on this principle, Dirac concluded that the constant of gravitation is not truly constant but decreases slowly in time.

The quantum theorist Max Born did not share Dingle's empiricist philosophy of science, and yet he felt it necessary to warn against the aprioristic elements in the Milne–Eddington style of cosmophysics. 'My advice', he said in 1943, 'is not to rely on abstract reason, but to decipher the secret language of Nature from Nature's documents, the facts of experience'.[10]

The debate concerning the scientific status of cosmological theories continued after the Second World War, now with a focus on the steady-state theory proposed in 1948 in two different versions, one by Hoyle and the other by Bondi and Gold. The Bondi–Gold version was explicitly deductivist and based on the perfect cosmological principle, that is, the claim that the universe is uniform on a large scale with respect to both space and time. Although Bondi and Gold did not consider the principle to be of an a priori nature, they did claim that 'if it does not hold, one's choice of the variability of the physical laws becomes so wide that cosmology is no longer a science'. They believed that the principle was of such fundamental importance that 'we shall be willing if necessary to reject theoretical extrapolations from experimental results if they conflict with the perfect cosmological principle even if the theories concerned are generally accepted'.[11]

It followed from the basic assumptions of the steady-state theory that matter had to be created continually throughout space, although at such a small rate (about 10^{-43} g/s/cm^3) that it was not directly detectable. The associated concepts of the perfect cosmological principle and continual creation of matter were widely seen as problematic, even provocative, and did much to make the theory controversial. Dingle resumed his earlier critique against rationalistic cosmology, declaring that the steady-state theory was nothing but a mathematical fancy, an unfortunate case of unscientific romanticizing. The theoretical astronomer George McVittie similarly concluded that the theory was not truly scientific and that its postulate of matter creation violated the basic rules of scientific reasoning. 'It's like breaking the rules when you are playing a game', he said in an interview of 1978. 'If you allow yourself in the game of American football to take knives on board with you and stab your opponent, now and again, of course the results will be very remarkable, particularly if one side only has the knives and the other is merely the recipient'.[12]

In the evaluation of the steady-state theory in relation to relativistic evolution theories, theoretical and metascientific arguments played no less significant a role than comparison of predictions with observations. The space of the steady-state universe is flat and exponentially expanding, and for this reason it contains infinitely many regions of galaxies with no causal connection between them. Gerald Whitrow, among others, pointed out that this leads to bizarre and epistemically problematic consequences. Not only did the theory postulate a multitude of galaxies that always have and always will be beyond empirical detection, it also seemed to lead to inconsistency with the very conceptual foundation of the theory, the perfect

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[10] Max Born, *Experiment and Theory in Physics* (Cambridge, 1943), 44.

[11] Hermann Bondi and Thomas Gold, 'The Steady-State Theory of the Expanding Universe', *Monthly Notices of the Royal Astronomical Society*, 108 (1948), 252–70, p. 254. The emergence and historical development of the steady-state theory, including the philosophical objections to it, is detailed in H. Kragh, *Cosmology and Controversy: The Historical Development of Two Theories of the Universe* (Princeton, NJ, 1996), where further references can be found.

[12] Interview by David DeVorkin, American Institute of Physics, 21 March 1978. Quoted in Kragh (note 11), 249.

cosmological principle. In regard of such weirdness, could the theory be considered a serious candidate for a scientific cosmology?[13]

The main point to note is that for a decade or more there was a heated discussion concerning the criteria of science appropriate for cosmological theories, including the question of whether cosmology could ever become a proper science. It was sometimes objected that the steady-state theory failed to live up to standard criteria of science, whereas advocates of the theory maintained that it did and was in fact preferable from an epistemic and methodological point of view. Both parties agreed that a cosmological theory, if of scientific worth, should include the possibility of observational disproof. Bondi, in particular, stressed the virtues of Karl Popper's falsificationist philosophy which he considered to be methodological support of the steady-state theory. After all, this theory led to several unique and testable predictions, whereas the rival class of relativistic models was not in the same way vulnerable to refutation. Here is how Bondi, the faithful Popperian, thought about the scientific status of cosmology:

> Although the adherents of some theories are particularly concerned with pointing out the logical beauty and simplicity of their arguments, every advocate of any theory will always be found to stress especially the supposedly excellent agreement between the forecasts of this theory and the sparse observational results. The acceptance of the possibility of experimental and observational disproof is as universal and undisputed in cosmology as in any other science, and, though the possibility of logical disproof is not denied in cosmology, it is not denied in any other science either. By this test, the cardinal test of any science, modern cosmology must be regarded a science.[14]

Bondi's admiration for Popper's philosophy of science was boundless. In 1992, on the occasion of Popper's ninetieth birthday, he summarized his view in a single sentence: 'There is no more to science than its method, and there is no more to its method than Popper has said'.[15]

In spite of accusations from some antagonistic scientists and philosophers, the steady-state theory was not really an attempt to establish a new paradigm of physical cosmology. In this respect it differed from the earlier and more radical theories of Eddington and Milne. On the contrary, from an epistemic point of view the theory was conservative in so far as it emphasized the crucial role of empirical testability. Not only was the steady-state theory vulnerable to falsification, it was in fact falsified by observations such as counts of radio sources and, in 1965, the discovery of the cosmic microwave background.

3. Brief history of the multiverse

Speculations concerning multiple worlds, either in a spatial or a temporal sense, can be traced back to the pre-Socratic philosophers, when such ideas were first discussed by Anaximander and Anaximenes. In the late renaissance, they figured prominently in the cosmology of Giordano Bruno and since then ideas of multiple

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[13] Gerald J. Whitrow, *The Structure and Evolution of the Universe* (New York, 1959), 138–41.

[14] G.J. Whitrow and H. Bondi, 'Is Physical Cosmology a Science?' *British Journal for the Philosophy of Science*, 4 (1954), 271–83, p. 279.

[15] H. Bondi, 'The Philosopher for Science', *Nature*, 358 (1992), 363.

worlds have been a standard ingredient in cosmological speculations. They appear, for example, in the eighteenth-century scenarios of Thomas Wright and Immanuel Kant. The most discussed of these speculations is probably the scenario considered by Ludwig Boltzmann in 1895 in connection with the thermodynamic state of the universe predicted by the law of entropy increase. In effect, the Austrian physicist suggested that a sufficiently large universe would consist of a multitude of separate subuniverses, some of which (including our own) would be in low-entropic states while the universe as a whole would be in an equilibrium state corresponding to maximum entropy.[16]

Within the tradition of twentieth-century relativistic cosmology the notion of many universes may first have been mentioned by Eddington, shortly after the notion of the expanding universe had been introduced in cosmology. In a paper of 1931 he pointed out that the accelerated expansion of the closed Lemaître-Eddington universe would eventually lead to a situation where 'Objects separating faster than the velocity of light are cut off from any causal inference on one another, so that in time the universe will become virtually a number of disconnected universes no longer bearing any physical relation to one another'.[17] At about the same time the Japanese physicist Tokio Takeuchi presented the first relativistic model of a temporal multiverse, that is, a cyclic universe with an infinite number of cycles.[18] A few years later, Richard Tolman, while examining inhomogeneous models (not satisfying the cosmological principle), noticed the possibility of a universe containing independent homogeneous regions of different density and curvature. Some of these regions, he wrote, 'might be contracting rather than expanding and contain matter with a density and stage of evolutionary development quite different from those with which we are familiar'.[19]

Thus, as early as the 1930s several versions of multiple universe models, most of them building on Einstein's field equations, had entered the cosmological literature. Other models were considered in the 1960s, primarily by Jaroslav Pachner in Poland, Ronald G. Giovanelli in Australia, and Hoyle and Jayant Narlikar in England. According to Pachner, 'We shall suppose the existence of many closed universes so embedded into the 'cosmical space of higher number than four' that their hypersurfaces do not intersect each other. Since there exists no physical interaction under [*sic*] them, they are incapable of being observed, but this does not signify that they do not exist'.[20]

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[16] Ludwig Boltzmann, 'On Certain Questions of the Theory of Gases', *Nature*, 51 (1895), 413–15. For a recent analysis, see M.M. Ćirković, 'The Thermodynamical Arrow of Time: Reinterpreting the Boltzmann-Schuetz Argument', *Foundations of Physics*, 33 (2003), 467–90. A valuable historical review of multiple universe cosmologies, focusing on the modern period, is provided in Stefano Bettini, 'A Cosmic Archipelago: Multiverse Scenarios in the History of Modern Cosmology', ArXiv:physics/051011 (2005). The address of the ArXiv e-print archive, much used by physicists, is http://arxiv.org/

[17] A.S. Eddington, 'The Expansion of the Universe', *Monthly Notices of the Royal Astronomical Society*, 91 (1931), 412–16, p. 415. The Lemaître-Eddington model, originally proposed by Georges Lemaître in 1927, includes a positive cosmological constant and expands asymptotically from an Einstein state.

[18] Tokio Takeuchi, 'On the Cyclic Universe', *Proceedings of the Physico-Mathematical Society of Japan*, 13 (1931), 166–77. A single-cycle model was discussed by Alexander Friedmann in his classical paper of 1922, but without extending it to a series of many cycles. Takeuchi's model avoided cosmic singularities and thus allowed one universe to grow out of the fossils of the previous one. For a historical survey of cyclic models in relativistic cosmology, see H. Kragh, 'Continual Fascination: The Oscillating Universe in Modern Cosmology', *Science in Context*, 22 (forthcoming 2009).

[19] Richard C. Tolman, 'Effect on Inhomogeneity in Cosmological Models', *Proceedings of the National Academy of Sciences*, 20 (1934), 169–76, p. 175. Reprinted in *General Relativity and Gravitation*, 29 (1997), 935–43.

[20] Jaroslav Pachner, 'Dynamics of the Universe', *Acta Physica Polonica*, 19 (1960), 662–73, p. 673.

In the revised steady-state theory proposed by Hoyle and Narlikar in 1966, the authors were led to consider separate and continually forming bubble universes of which our own was just one bubble among others. Hoyle speculated that the known physical properties, say the mass ratio between the proton and the electron, might reflect the size of the particular universe we live in. 'If their values were different in other localities the full range of the properties of matter would be incomparably richer than it is usually supposed to be', he commented.[21]

The few and scattered proposals of multiverse-like ideas before 1980 attracted little attention, and this was also the case with Brandon Carter's later so influential suggestion of 1974 of a world ensemble—'an ensemble of universes characterised by all conceivable combinations of initial conditions and fundamental constants'—in which he introduced the modern formulation of the anthropic principle.[22] Although many-universe ideas were well known, and disseminated to a broader public in popular books such as Paul Davies' *Other Worlds* from 1980, the majority of cosmologists considered them heterodox and speculative. The inflation theory of the very early universe did much to change the situation, especially in the versions of 'chaotic' and 'eternal' inflation introduced by the Russian physicists Andrei Linde and Alexander Vilenkin in the early 1980s.[23] Thus, Linde concluded in 1982 that after the brief inflation phase, the universe became divided into an infinity of bubble- or subuniverses. Among the first to investigate inflationary cosmology as a theory of many universes was J. Richard Gott, who the same year proposed a model that 'makes it possible to create from the original de Sitter space other $k = -1$ universes (perhaps an infinite number) which are entirely disjoint from our own and from each other'.[24]

Linde likened his chaotic inflationary scenario to an infinite chain reaction with no end and possibly no beginning either. In an important paper of 1986 he made it clear that the thought of the universe as a multiverse: 'An enormously large number

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[21] F. Hoyle and J. Narlikar, 'A Radical Departure from the "Steady-State" Concept in Cosmology', *Proceedings of the Royal Society* (London), 290 (1966), 162–76; F. Hoyle, *Galaxies, Nuclei, and Quasars* (New York, 1965), 131. On the Hoyle-Narlikar theory, see also Kragh (note 11), 366–68.

[22] Brandon Carter, 'Large Number Coincidences and the Anthropic Principle in Cosmology', in *Confrontation of Cosmological Theories with Observational Data*, edited by Malcolm S. Longair (Dordrecht, 1974), 291–98. The general idea of the anthropic principle is that the observed universe is conditioned by the existence of complex life forms such as human observers. As a selection principle it claims that the constants and parameters of our universe are fine-tuned to permit the emergence of life, especially intelligent life. The principle exists in several versions and has given rise to a wealth of literature, both scientific, philosophical and theological.

[23] Inflationary models assume the existence of a primordial 'false vacuum' which expands at a phenomenal rate and after a split second blows up the universe by a gigantic factor. At the end of the brief inflation phase, the false vacuum decays to a normal vacuum state and attractive gravity replaces the repulsive force. Although the basic ideas of inflationary cosmology were suggested in the late 1970s, the hypothesis only took on with Alan Guth's development of it in 1981. The early history of inflation is described in Chris Smeenk, 'False Vacuum: Early Universe Cosmology and the Development of Inflation', in *The Universe of General Relativity*, edited by A.J. Kox and Jean Eisenstaedt (Boston, 2005), 223–58. See also the critical review in John Earman and Jesus Mosterin, 'A Critical Analysis of Inflationary Cosmology', *Philosophy of Science*, 66 (1999), 1–49. The main reason for the nearly paradigmatic status of inflationary models in modern early-universe cosmology is that inflation leads to a density perturbation spectrum in excellent agreement with precision measurements of the cosmic background radiation. This is remarkable, but not a proof that an inflationary era actually occurred. The same result can be obtained without assuming the dynamical mechanism of inflation models: Stefan Hollands and Robert M. Wald, 'An Alternative to Inflation', *General Relativity and Gravitation*, 34 (2002), 2043–55.

[24] J. Richard Gott, 'Creation of Open Universes from de Sitter Space, *Nature*, 295 (1982), 304–5, p. 304. The quantity k denotes the curvature parameter which can attain the values $+1$ (closed universe), 0 (flat universe) or -1 (open universe).

of possible types of compactification which exist e.g. in the theory of superstrings should be considered not as a difficulty but as a virtue of these theories, since it increases the probability of the existence of mini-universes in which life of our type may appear'.[25] By 1990 there existed a variety of ideas of how multiple universes might be generated. Some of them were based on inflation theory, others on hypotheses of cyclic universes, and others again on the many-worlds interpretation of quantum mechanics. I shall focus on the first class of multiverse.

A few of the multiverse theories proposed in the 1980s were motivated by attempts to explain various anthropic coincidences, but this was not generally the case. Not only are the two approaches, the one based on multiverse scenarios and the other on the anthropic principle, logically distinct from one another, they were rarely seen as connected until the last decade of the century. Indeed, inflation cosmology was often seen as an alternative to anthropic reasoning because it might seem to make anthropic explanations redundant. Only later did it become common to conceive inflation as a justification of the anthropic principle and at the same time a modification of it.

4. Modern concept of the multiverse

According to the self-reproducing or eternal inflationary scenario, pocket or bubble universes will be produced constantly from regions of false vacuum and the universe (or multiverse) as a whole will regenerate eternally. Vilenkin claims that inflationary cosmology, at least in his favoured eternal version, makes the multiverse 'essentially inevitable', a claim supported by other multiverse enthusiasts.[26] Thus, Alan Guth, the primary originator of inflation theory, came to share the belief of Linde, Vilenkin and others that inflation means multiplicity of universes. 'Given the plausibility of eternal inflation', he wrote in a popular exposition of 1997, 'I believe that soon any cosmological theory that does not lead to eternal reproduction of universes will be considered as unimaginable as a species of bacteria that cannot reproduce'.[27] Guth is convinced that inflation leads eternally to new pocket universes. As he formulates it in a recent paper, 'Once inflation happens, it produces not just one universe, but an infinite number of universes'.[28] As he and others have pointed out, in such an infinite multiverse anything that can happen will happen—and it will happen infinitely often. According to Guth's analysis of eternal inflation, inflation will go on forever in the future, but it is not eternal in the past, meaning that *the* big bang is still part of the theory.

Among the cosmologists of the older generation who adopted the multiverse idea was Dennis Sciama, an eminent astrophysicist who in his early career had advocated the steady-state programme. Sciama suggested that the existence of many worlds was necessary not only to explain the fine-tuning of natural constants but also to explain why the possibility of many other universes did not, apparently, correspond to the physical reality of these possibilities. In an interview he phrased his belief as follows: 'Any logically possible universe exists, not just for anthropic reasons.... It's much

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[25] Andrei Linde, 'Eternally Existing Self-Reproducing Chaotic Inflationary Universe', *Physics Letters* B, 175 (1986), 395–401, p. 399.

[26] Alexander Vilenkin, 'Anthropic Predictions: The Case of the Cosmological Constant', in *Universe or Multiverse?* edited by Bernard Carr (Cambridge, 2007), 163–80, p. 163.

[27] Alan H. Guth, *The Inflationary Universe* (Reading, MA, 1997), 252.

[28] A.H. Guth, 'Eternal Inflation and its Implications', ArXiv:hep-th/0702178 (2007).

more satisfying to say that there is *no* constraint on the universe. All logically possible cases are realized, and we're in one of the few that allow us'.[29]

Since the beginning of the new century there has been a marked change in the interest for and attitude to the multiverse, with many eminent physicists having 'converted' from the idea of a single universe to the possibility of many universes. Part of the reason has been the increased focus on the cosmological constant as a vacuum energy that followed the discovery in 1998 of the accelerated expansion of the visible universe. Another important reason, apart from the inflation theory, is that advances in string theory (or M theory) have inspired confidence in the multiverse. As mentioned, the idea of relating the multiverse to concepts of string theory was suggested by Linde in 1986, but it only appeared in an elaborate form several years later. In a paper of 2000 two string physicists demonstrated that 'multiple four-form strengths arise in most M theory compactifications, and that these could lead to a spectrum of effective cosmological constants sufficiently finely spaced that some would lie in the observational range'.[30] That is, a very large number of vacuum states might explain the problem of the size of the cosmological constant without direct appeal to fine-tuning.

It now seems that there is no unique way in which string theory can predict all the constants of nature by 'compactifying' the six extra dimensions that are additional to the four dimensions of our space–time. Each of these compactifications corresponds to a distinct vacuum state and may be taken to represent a possible world with its own laws and constants of physics. This theory of a 'landscape' of universes has been developed and promoted by, among others, Leonard Susskind, a Stanford theorist and one of the founding fathers of string theory.[31] The string landscape provides the possibility for an enormous amount of universes, and eternal inflation provides a mechanism for generating these universes. According to Susskind, the number of different vacuum states or possible universes that come out of string theory is a staggering 10^{500} or more. These are claimed to be really existing or parts of the 'populated' landscape.[32]

There are several ways in which to classify multiverse theories, but none that has won general recognition. Nor is there, for that matter, consensus as to what constitutes or defines a multiverse. According to Laura Mersini-Houghton it is completely theory dependent, namely 'the ensemble of all possible universes predicted by the underlying theory'.[33] A simple classification has been proposed by George Gale, who distinguishes

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[29] Quoted from an interview of 1989 in Alan I. Lightman and Roberta Brawer, *Origins: The Lives and Worlds of Modern Cosmologists* (Cambridge, MA, 1990), 151.

[30] Raphael Bousso and Joseph Polchinski, 'Quantization of Four-Form Fluxes and Dynamical Neutralization of the Cosmological Constant', *Journal of High Energy Physics*, 06 (2000), 006. One of the most challenging problems of theoretical physics is to explain why the cosmological constant is so much smaller than the vacuum energy calculated by the quantum theory of elementary particles. This energy is at least 120 orders of magnitude greater than what is indicated by astronomical observations! For an accessible review of the string-based multiverse and other ideas of multiple universes, see P.C.W. Davies, 'Multiverse Cosmological Models', *Modern Physics Letters*, A 19 (2004), 727–44.

[31] Leonard Susskind, 'The Anthropic Landscape of String Theory', ArXiv:hep-th/0302219 (2003); L. Susskind, *The Cosmic Landscape: String Theory and the Illusion of Intelligent Design* (New York, 2006). See also R. Bousso and J. Polchinski, 'The String Theory Landscape', *Scientific American*, 290 (September 2004), 60–69.

[32] Susskind's notion of existence is problematic and probably not shared by most other physicists: 'What physicists . . . mean by the term *exist* is that the object in question can exist *theoretically.* In other words, the object exists as a solution to the equations of the theory. By that criterion perfectly cut diamonds a hundred miles in diameter exist. So do planets made of pure gold. They may or may not actually be found somewhere, but they are possible objects consistent with the Laws of Physics'. Susskind 2006 (note 31), 177.

[33] Laura Mersini-Houghton, 'Thoughts on Defining the Multiverse', ArXiv:0804.4280 (2008).

between (1) spatial multiverse models, (2) temporal multiverse models, and (3) models with universes of other dimensions.[34] The second class comprises cyclic models, new versions of which have recently attracted considerable attention.[35] In some of these models the current and previous cycles are physically unconnected in the sense that no information from the previous universe passes over to the successor universe; in other models the new universe has some memory of its predecessor.

The simplest spatial multiverse is not very exotic as we only have to refer to our own universe, assuming that it is flat and infinite and satisfying the cosmological principle. The classical Einstein-de Sitter universe of 1932, which expands 'critically' as $R \sim t^{2/3}$, might be one example. If accelerated expansion is also assumed, such as strongly suggested by recent observations, there will be an infinity of causally disjoint regions or subuniverses with all the conceptual problems that come along with a realized infinite ensemble.[36] This relatively uncontroversial kind of multiverse is the first level in Tegmark's influential four-level hierarchy of multiverse models including universes increasingly more exotic and different from the one we know.[37] Whereas there is only one big bang in class I, in class II there are many big bangs, such as exemplified in different ways by eternal inflationary theories and the Steinhardt–Turok oscillating model. Class III is essentially the universes associated with the Everett many-worlds interpretation of quantum mechanics.

More extreme is Tegmark's 'Platonist paradigm' of class IV multiverse models, according to which the various universes are not only governed by different physical laws and constants but also by different mathematical structures. It is postulated—and of course it is nothing but a philosophical postulate—that any mathematically possible universe has physical reality and must exist somewhere. According to Tegmark, 'mathematical democracy' requires that mathematical existence and physical existence must be equivalent.[38] Most of the current discussion of the multiverse is related to class II models, where the individual universes have different constants of nature but are supposed to follow the same fundamental laws of physics. They cannot exist if they violate these laws.

The universes generated by eternal inflation have a common causal origin and share the same space–time, for which reason they do not form a completely disconnected multiverse. Nor is this the case for cyclic models of the Steinhardt-Turok type. The other universes are not accessible to observers located in our universe but are nonetheless connected, which distinguishes this kind of multiverse from ideas of a genuine multiverse made up of strictly disjoint universes such as proposed by Tegmark and others. It is only in the first case that regular properties

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[34] G. Gale, 'Cosmological Fecundity: Theories of Multiple Universes', in *Physical Cosmology and Philosophy*, edited by John Leslie (New York, 1990), 189–206.

[35] Paul J. Steinhardt and Neil Turok, *Endless Universe: Beyond the Big Bang* (New York, 2007). See also Kragh 2009 (note 18).

[36] On these problems, see George F.R. Ellis and G.B. Brundrit, 'Life in the Infinite Universe', *Quarterly Journal of the Royal Astronomical Society*, 20 (1979), 37–41. For a sharper version, based on inflation theory, see Jaume Garriga and A. Vilenkin, 'Many Worlds in One', *Physical Review* D, 64 (2001), 043511.

[37] M. Tegmark, 'Parallel Universes', *Scientific American*, 288 (May 2003), 41–51; M. Tegmark, 'The Universe Hierarchy', in Carr 2007 (note 26), 99–125.

[38] Tegmark originally discussed his 'ultimate ensemble theory' in 1998, at that time without referring to the multiverse as justified by inflationary models. 'Everything that exists mathematically exists physically', he claimed, arguing that his radically Platonist theory has genuine predictive power and lives up to Popper's falsifiability requirement. M. Tegmark, 'Is "the Theory of Everything" Merely the Ultimate Ensemble Theory?' *Annals of Physics*, 270 (1998), 1–51, p. 2.

across the ensemble of universes can be expected. Although some scientists take care to distinguish between the two classes of multiverse,[39] many do not. To avoid unnecessary confusion, it has been suggested to reserve the term 'multiverse' for the second class and use the name 'multi-domain universe' for the first class, but few authors follow this terminology.

Multiverse physics, in its widest sense, leads to an entirely new conception of *laws of nature* and the relationship between law-bound and contingent phenomena. Physicists are used to think that the fundamental laws—whether we know them or not—are the unique and first principles from which natural phenomena can be calculated. But according to multiverse thinking there is nothing particularly elevated about the laws that govern our universe; they are merely local and anthropically allowed by-laws, that is, consistent with life as we know it.[40] From the grander perspective of the multiverse they are contingent and so are the values of at least some of the physical parameters. Rather than accepting that the environment is determined by the laws of nature, multiverse physicists suggest that the laws are determined by the environment.

5. Testability and unobservable worlds

The increasing popularity of multiverse cosmology and anthropic arguments has caused much debate in the physics community. Several conferences have been held on the subject, the most important of which took place at Oxford University in 2003, and it has been discussed in a large number of papers and books, scientific as well as popular. The overarching question is as simple as it is crucial: Is multiverse cosmology a science? All physicists agree that a scientific theory has to speak out about nature in the sense that it must be empirically testable, but they do not always agree what testability is or how important this criterion is relative to other criteria.

In his early defense of the multiverse, dating from 1993, Sciama considered some of the potential objections against the hypothesis, including the following.[41] (i) The hypothesis is much too extravagant and bizarre to be credible. (ii) It violates the well established tradition in theoretical physics to explain phenomena deductively from a fundamental theory. (iii) The multiverse hypothesis has no real predictive power. (iv) It is pointless or unscientific to postulate the existence of other universes, many of which are unobservable even in principle. These are some of the objections that are discussed among scientists in the recent debate concerning the multiverse.

With regard to the first point, although the multiverse is certainly bizarre, this cannot in itself be a valid objection against the hypothesis. Nonetheless, arguments based on epistemic or ontological weirdness do play a role and may contribute to the overall assessment of a theory. As mentioned, this was the case in the controversy over the steady-state theory where Whitrow and others objected to the multiverse features of the theory. The multitude of parallel universes may seem to be wasteful and hence to violate the principle of simplicity accepted by most scientists. However, this principle is notoriously ambiguous and offers little guide for choosing between

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[39] E.g., G.F.R. Ellis, U. Kirchner and W.R. Stoeger, 'Multiverses and Physical Cosmology', *Monthly Notices of the Royal Astronomical Soc*iety, 347 (2004), 921–36.

[40] Martin Rees, *Our Cosmic Habitat* (London, 2003), 172–75.

[41] D.W. Sciama, 'Ist das Universum eigenartig?', in *Vom Urknall zum komplexen Universum*, edited by Jürgen Ehlers, Gerhard Börner and Heinrich Meier (Munich: Piper, 1993), 183–94, pp. 192–94.

theories. Tegmark has argued that the multiverse is not really wasteful and that there is a sense in which it is simpler than any of its constituent universes.[42]

A related problem, which was also discussed during the cosmological controversy in the 1950s, is the infinite number of universes that is part of at least some multiverse scenarios. According to George Ellis, a distinguished South African cosmologist, this 'extraordinarily extravagant proposal' is philosophically unacceptable and a main reason why cosmological models of this type must be dismissed as candidates for really existing universes.[43] Actual infinities have no place in either cosmology or any other science. As Ellis and his collaborators realize, this is a philosophical and conceptual argument and not one which can be answered on purely scientific grounds.[44]

I shall now refer to some of the reasons for and against the hypothesis of a multiverse. As Martin Rees, distinguished astrophysicist and Astronomer Royal of Great Britain, has pointed out at several occasions, there is a blurred transition between what can be directly observed and what is strictly unobservable.[45] We have no problem in accepting that galaxies which have crossed the visible horizon, dependent only on the power of telescope technology, are still real parts of the universe; nor have we serious problems with conceiving galaxies passing beyond the horizon corresponding to an infinite redshift. If so, there may be but a small step to accept the existence of galaxies that disappear at an ever increasing rate, as in the case of an accelerated expansion of space, although these are and forever remain unobservable in principle. We may now compare these causally disjoint regions—which we hold to be real—with other disjoint regions that emerge from separate big bangs, as in eternal inflation. If we have confidence in the reality of the first class of regions, why not believe in the reality of the second class as well? Rees believes that this shows that the existence of other universes is a scientific question. Summarizing what is known as the 'slippery slope argument' he writes: 'From a reluctance to deny that galaxies with redshift 10 are proper objects of scientific enquiry, you are led towards taking seriously quite separate spacetimes, perhaps governed by quite different laws'.[46]

The slippery slope argument may be more seductive than compelling. For one thing, it tacitly assumes that 'observability in principle' is the same as 'reality', which is a categorial mistake.[47] For another thing, it ignores the conceptual discontinuity between unobservable galaxies in our universe and those in separate space–times with origins in separate big bangs.

One obvious objection against multiverse theories is that they claim the existence of a multitude of universes which are in principle unobservable. How can we possibly justify their existence? On the other hand, so one answer goes, there have been earlier

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[42] Tegmark 1998 (note 38), 44 and Tegmark 2007 (note 26), 123.

[43] Ellis, Kirchner and Stoeger 2004 (note 39), p. 932. Similarly in W.R. Stoeger, G.F.R. Ellis and U. Kirchner, 'Multiverses and Cosmology: Philosophical Issues', ArXiv:astro-ph/0407329 (2006) and G.F.R. Ellis, 'Multiverses: Description, Uniqueness, and Testing', 387–410 in Carr 2007 (note 26).

[44] Discussed as much in religious and philosophical contexts as in a scientific context, the problem of infinities in cosmology goes back a long time. For example, it was seen as a major problem in the late-nineteenth century controversy about a universe governed by the law of entropy increase. Generally speaking, whereas materialists insisted that the universe is spatially infinite, scientists of a theist inclination were in favour of a finite universe. H. Kragh, *Entropic Creation: Religious Contexts of Thermodynamics and Cosmology* (Aldershot, 2008), 93–96. Some of the arguments discussed in modern cosmology can be found almost identically in the older literature.

[45] Rees 2003 (note 40), 166; M. Rees, 'Cosmology and the Multiverse', in Carr 2007 (note 26), 57–76.

[46] Rees 2007 (note 45), 63.

[47] Stoeger, Ellis and Kirchner 2006 (note 43), 28.

cases in the history of science of predictions of unobservable entities and phenomena, and we have confidence in some of these. A theory cannot be considered scientific if all its predictions concern unobservable entities, but if only some of them are observable and testable matters are different. A well established theory with empirical successes may include predictions which cannot be tested, and in such a situation we have reason to believe in them in spite of their hypothetical nature. In somewhat different versions, the argument is common among multiverse proponents. According to Don Page, a physicist of the University of Alberta, 'One cannot test scientifically a theory that makes predictions about what is unobservable, but one can test a theory that makes use of unobservable entities to explain and predict the observable ones'.[48] Another formulation of the argument goes as follows:

> We will believe in them [unobservable universes] if they are predicted by a theory that gains credibility because it accounts for things we can observe. We believe in quarks, and in what general relativity says about the inside of black holes, because our inferences are based on theories corroborated in other ways. Specifically, if a theory has testable and falsifiable predictions in the observable part of the universe, we should seriously consider and be prepared to accept its predictions in parts of the universe (or multiverse) that are not accessible to direct observations.[49]

The comparison with quarks is misleading, as physicists' belief in them is based on experiments and not purely on theory. Although quarks cannot be isolated, they can and have been detected. Moreover, one can easily come up with historical counter-examples illustrating the danger of believing in things just because they are 'based on theories corroborated in other ways'. The phlogiston theory of the eighteenth century was empirically successful, yet it built on a non-existing entity; likewise, the electromagnetic ether of the late nineteenth century had a very high degree of credibility, yet the ether does not exist.

Apart from these and other counterexamples, it is questionable if string and inflation theories have the same credibility as well tested theories such as general relativity and quantum chromodynamics. The physics behind the multiverse hypothesis, whether based on the string landscape or eternal inflation, is extrapolated from known physics to quite new regimes. The multiverse does not follow from known and tested physical theory, but from hypothetical physics, and in any case it involves an extrapolation for which there is no independent justification.[50]

Whereas critics of the multiverse claim that predictions of many universes escape testing, proponents of the idea argue that it is testable, albeit not in the ordinary sense known from physics. A multiverse theory may be trivially falsifiable if it is specific enough, say that it predicts that all the universes are devoid of oxygen.[51] Such a theory is not only falsifiable, it is falsified. More generally, a multiverse theory can be ruled out if it predicts that none of the universes in its ensemble have properties observed in our world. Unfortunately, real multiverse theories are anything but

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[48] Don Page, 'Predictions and Tests of Multiverse Theories', in Carr 2007 (note 26), 411–30, p. 413.

[49] Mario Livio and M.J. Rees, 'Anthropic Reasoning', *Science*, 309 (2005), 1022–23, p. 1023

[50] B. Carr and G.F.R. Ellis, 'Universe or Multiverse?', *Astronomy & Geophysics*, 49 (2008), 2.29–2.37, p. 2.34; G.F.R. Ellis, 'Dark Matter and Dark Energy Proposals: Maintaining Cosmology as a True Science?', ArXiv:astr-ph/0811.3529 (2008).

[51] Tegmark 2007 (note 37), 105.

specific and cannot be tested in this way. It is generally agreed that theories of the multiverse cannot result in definite predictions of the kind known from elementary particle theory and other parts of physics.

Nonetheless, proponents of the multiverse insist that predictions are possible and that these can be tested, only the predictions will appear in the form of probability distributions. However, it is extremely difficult to compute what fraction of an infinite set of universes includes a certain physical parameter.[52] The problem of how to define and compute probabilities in multiverse physics, that is, to calculate from a multiverse theory the probability that we should observe a given value for some physical property or constant of nature, is known as the 'measure problem'. It first turned up in the 1990s in connection with eternal inflation, where physicists asked if unambiguous probabilities can be assigned to constants varying from universe to universe.[53]

The measure problem is a hot topic in current research, but in spite of much work it has not led to real progress. Aurétien Barrau, a French physicist and advocate of the multiverse, admits that 'Except in some favourable cases, … it is hard to refute explicitly a model in the multiverse'. Yet he optimistically adds: 'But difficult in practice does not mean intrinsically impossible'.[54] Physicists seem to agree that although it is possible to derive probability predictions from a multiverse theory, this can be done only if certain strict conditions are satisfied. These conditions do not hold if the laws of physics vary from universe to universe (as in Tegmark's level IV), in which case no predictions of any kind appear to be possible.

6. Modifying the standards of science

If the multiverse theory does not agree with established norms of science, can't we just modify those norms? Anyway, what are these criteria that supposedly delimit science from non-science and why are they considered to be so authoritative? An acceptable physical theory has to lead to testable predictions, that is, statements that can be compared with observations and experiments, but it is generally agreed both among scientists and philosophers that there are other factors at play than mere empirical testing. We can have good reasons for believing in a theory even though it does not lead to *directly* testable consequences. Almost all physicists agree that a satisfactory theory, in addition to being testable, must also be simple and internally consistent, it must show explanatory power, and it must connect to the rest of science.[55] Where the waters divide is when it comes to the priority given to these criteria. Is empirical testability absolutely necessary? And, if this is granted, how should testability be understood?

Several of the proponents of the multiverse and anthropic reasoning suggest that physics is at a crossroads, on its way to shift from one paradigm to another—Kuhnian phrases occur abundantly in the literature. Perhaps 'we are facing a deep change of paradigm that revolutionizes our understanding of nature and opens new fields of

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[52] Anthony Aguirre, 'Making Predictions in a Multiverse: Conundrums, Dangers, Coincidences', in Carr 2007 (note 26), 323–66.

[53] A. Vilenkin, 'Unambiguous Probabilities in an Eternally Inflating Universe', *Physical Review Letters*, 81 (1998), 5501–04.

[54] Aurélien Barrau, 'Physics in the Universe', *Cern Courier*, 20 November 2007.

[55] These are the four criteria for a good theory proposed in G.F.R. Ellis, 'The Unique Nature of Cosmology', in *Revisiting the Foundations of Relativistic Physics*, edited by Abhay Ashketar et al. (Dordrecht, 2003), 193–220, p. 212.

possible scientific thought'.[56] The Nobel laureate Steven Weinberg and others are ready to accept multiverse theories based on the anthropic principle as a new style of physics which in some areas replaces the computational-experimental style based on first principles. They realize that this is a retreat from traditional epistemic values, perhaps an expression of defeatism, but more or less reluctantly resign themselves to it.[57]

As mentioned above, one way of changing the standards of science in a direction more suitable for the multiverse is to accept probabilistic in-principle testing. Another is to make use of new kinds of evidence and new epistemic rules, such as the philosopher Nick Bostrom has proposed with what he calls the self-sample assumption.[58] Assessment of a theory in physics typically involves considerations of coherence and mathematical consistency. To the extent that string theory can be said to have been tested, so far it has exclusively been done in this way. Susskind suggests that the same kind of non-empirical testing may apply to some multiverse models and in particular to the landscape model.[59]

William Stoeger, a Jesuit cosmologist critical to the multiverse, has suggested that although multiverse theories are not testable in the ordinary sense, they may well be scientific according to other notions of science.[60] At least potentially, they may be *retroductively testable*, a reference to Charles S. Peirce's idea of retroduction (also known as abduction). Here, the inference is from data to hypotheses rather than the other way around. According to Peirce's scheme, empirical data are explained by means of a theoretical model which typically will include unobserved or even unobservable entities. Some of the results derived from the model can be tested empirically and will, if they are confirmed, increase one's confidence in the key hypotheses of the model. As a consequence, one will have reasons to believe that the unobserved entities really exist. What matters in the scientific process is to construct a theory which is (i) empirically adequate; (ii) theoretically fruitful; (iii) consistent, both internally and with other established theories; and (iv) a source of further explanatory success. If a theory satifies requirements such as these, it is confirmed retroductively. It is considered provisionally reliable in the sense that it gives a good account of the reality it is purported to deal with. The unobserved entities may remain unobserved, and may remain so forever, but we will nonetheless have reason to believe that they exist.[61]

Stoeger does not conclude that the hypothesis of other universes is in fact retroductively supported, but he suggests that it has the potential of such support, namely if it turns out to be fruitful in the long run. Thus, some classes of the multiverse may be justified as scientific. This is the case with theories that refer to

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[56] Barrau 2007 (note 54).

[57] Steven Weinberg, 'Living in the Multiverse', in Carr 2007 (note 26), 29–42.

[58] Nick Bostrom, 'Self-Locating Belief in Big Worlds: Cosmology's Missing Link to Observation', *Journal of Philosophy*, 99 (2002), 607–23.

[59] Susskind 2006 (note 31), 375. The issue in the multiverse debate focuses on observational testing. Physicists active in quantum gravity research, including string theory, often speak of testing in a different sense, for example if results of classical general relativity can be derived as an approximation to a particular theory of quantum gravity. This is neither unusual nor controversial. It was an important test af Einstein's theory of gravitation that it led to Newton's theory in the limit of weak gravitational fields.

[60] W.R. Stoeger, 'Retroduction, Multiverse Hypotheses and their Testability', ArXiv:astro-ph/0602356 (2006); Stoeger, Ellis and Kirchner 2006 (note 43).

[61] For arguments in favour of retroduction in history and philosophy of science, see Ernan McMullin, *The Inference that Makes Science* (Milwaukee: Marquette University Press, 1992) and Russell N. Hanson, *Patterns of Discovery* (Cambridge, 1969), 85–90.

universes somehow connected to ours, whereas Stoeger argues that completely disjoint universes do not belong to the realm of science.

It is not often that the very nature of science comes up for discussion among scientists, but this is what is at stake here. Is the multiverse a scientific concept, a reality which follows nearly inevitably from fundamental physics? Or is it a speculation whose proper place is in philosophy departments and science fiction literature? Whereas Susskind supports the first claim, the leading antagonist George Ellis favours the second claim, maintaining that the existence of a multiverse 'remains a matter of faith rather than proof'.[62] In a discussion with Bernard Carr, he summarizes the larger perspectives of the dispute as follows:

> The very nature of the scientific enterprise is at stake in the multiverse debate. Its advocates propose weakening the nature of scientific proof in order to claim that the multiverse hypothesis provides a scientific explanation. This is a dangerous tactic. . . . Can one maintain one has a genuine scientific theory when direct and indeed indirect tests of the theory are impossible? If one claims this, one is altering the meaning of science. There are many other theories waiting in the wings, hopening for a weakening of what is meant by 'science'. Those proposing this weakening in the case of cosmology should be aware of the flood of alternative scientific theories whose advocates will then state that they too can claim the mantle of scientific respectability.[63]

That is, if multiverse cosmology is admitted as a science, why not astrology, intelligent design and crystal healing? We are back at the old question of a solid demarcation criterion of science, the traditional answer being empirical testability and, more specifically, falsifiability.

Scientific theories are supposed not only to make predictions but also to explain phenomena. Although some kinds of (nomological-deductive) explanation are equivalent to prediction, in general this is not the case. There are theories which have great explanatory power but rate poorly when it comes to testable and specific predictions. As Ellis and other critics have argued, multiverse theories are extreme in this respect since they offer no specific predictions and yet are able to explain about everything. A theory which operates with 10^{500} universes or more can accommodate almost any observation; and should the observational result be revised, it will have no problem with explaining that either. 'The existence of universes with giraffes is certainly predicted by many multiverse proposals, but universes where giraffes do not exist are also predicted'.[64] The mathematician Peter Woit, an outspoken critic of string theory, agrees that the string landscape is empirically vacuous: 'The theory can never predict anything and never be falsified'.[65]

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[62] Ellis, Kirchner and Stoeger 2004 (note 39), 935. See also G.F.R. Ellis, 'Issues in the Philosophy of Cosmology', in *Philosophy of Physics*, edited by Jeremy Butterfield and John Earman (Amsterdam, 2007), 1183–285, p. 1265. This is also the argument in Ronald G. Larson, 'Is "Anthropic Selection" Science?', *Physics in Perspectives*, 9 (2007), 58–69, who notes the similarity of multiverse thinking to Eastern religions. Similar accusations have for a couple of decades been directed at string theory, which according to some antagonists tends to replace science with faith and should belong to either departments of mathematics or schools of divinity. See quotations in Galison 1995 (note 3).

[63] Carr and Ellis 2008 (note 50), 2.33.

[64] Carr and Ellis 2008 (note 50), 2.35.

[65] Peter Woit, *Not Even Wrong* (London, 2007), 242.

Ellis recognizes of course that the accepted norms of science are not static and what has passed as legitimate science has changed over time and from one science to another. Nonetheless he insists that there is a core feature of science that must be retained at all cost, namely that scientific theories are empirically testable. Leave this criterion, and you have left science. Lee Smolin, a leading physicist at the Perimeter Institute in Canada, is no less adamant in his advocacy of falsifiability as a sine qua non of science. Referring to the lack of testability of the string landscape, he deplores that 'some of its proponents, rather than admitting that, are seeking leave to change the rules so that their theory will not need to pass the usual tests we impose on scientific ideas'.[66] Physicists sympathetic to the multiverse call attention to the methodological changes that have occurred throughout the history of science, and they are more willing to accept softened versions of the sacrosanct principle of testability. 'One needs some degree of falsifiability, but the question is, how much and how soon?'[67]

Among the antagonists of the multiverse and anthropic reasoning are Steinhardt and Turok, who argue that their own model of an infinite cyclic universe is methodologically superior to the inflationary multiverse. 'Science should remain based on the principle that statements have meaning only if they can be verified or refuted', they say, concluding that the multiverse fails miserably on this count.[68] Nor does it lead to a unique way of assessing the number of separate universes or their physical parameters. Steinhardt and Turok note with regret the trend towards accepting anthropic reasoning, 'but it seems likely to us to drag a beautiful science towards the darkest depths of metaphysics'.[69]

The current cosmological debate is in part about the legitimate standards of physical science and the role of speculations. Both parties accept that speculative ideas have an important part in science, and in cosmology in particular, but they disagree whether the multiverse proposal is speculative or not. And, if the multiverse is admitted as a speculation, whether it is a scientific or philosophical speculation. The critics argue that in the strong sense of an ensemble of totally disconnected universes, the multiverse theory certainly belongs to the latter class because it lacks the objectivity that must be crucial to any science. One may claim that there exists a universe in which electrons are heavier than protons, or is populated with tartan elephants, but such claims are necessarily non-scientific because they cannot be checked.

7. Role of philosophy

Cosmology has always been a field where metaphysical and other philosophical considerations have played a role. In spite of the great scientific progress that has occurred during the last century, parts of cosmology may still be more philosophical than scientific in nature. The two fields cannot be easily and cleanly separated.[70] As mentioned, critics of the multiverse concede that it is an interesting philosophical proposal but deny that it belongs to science proper. Ellis has emphasized that multiverse cosmology is fraught with philosophical problems and that it is important to recognize

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[66] Lee Smolin, *The Trouble with Physics* (London, 2008), 170.

[67] Carr and Ellis 2008 (note 50), 2.37.

[68] Steinhardt and Turok 2007 (note 35).

[69] P.J. Steinhardt and N. Turok, 'The Cyclic Model Simplified', ArXiv:astro-ph/0404480 (2004).

[70] E. McMullin, 'Is Philosophy Relevant to Cosmology?' *American Philosophical Quarterly*, 18 (1981), 177–89.

them as such. One of the problems is the infinite number of universes of some theories, which 'is primarily a conceptual or philosophical problem'.[71] We have also seen how philosophical criteria of science turn up in the cosmological debate, especially issues such as testability and falsifiability. Clearly, philosophy is part and parcel of the debate.

Should scientists pay attention to philosophical notions of what science is and how good science is done? More generally, who have the right to define the limits and proper methods of science? The philosophers or the scientists? This is not a new question, of course, and it has entered modern cosmology at several earlier occasions. For example, during the debate about the 'modern Aristotelians' in the 1930s (section 2) the physicist Charles Galton Darwin objected to those philosophers who 'tell us what we are allowed to think'. Is not, he asked rhetorically, 'the salient fact about the philosophy of science that no professional philosopher can write a book that a man of science wants to read?'. According to Darwin, scientists were better off ignoring philosophical rules and attempts at censuring scientific thinking: 'It is surely hard enough to make discoveries in science without having to obey arbitrary rules in doing so; in discovering the laws of Nature, foul means are perfectly fair'.[72]

Seventy years later, some multiverse physicists made about the same point. Provoked by the charges against the multiverse of being unfalsifiable, Barrau insists that science can only be defined by the scientists themselves: 'If scientists need to change the borders of their own field of research, it would be hard to justify a philosophical prescription preventing them from doing so'.[73] Susskind is another multiverse advocate who has little patience with armchair philosophy and philosophical demarcation criteria. 'As for rigid philosophical rules, it would be the height of stupidity to dismiss a possibility [like the string multiverse] just because it breaks with some philosopher's dictum about falsifiability'.[74] In an exchange of views with Smolin concerning the anthropic principle, he elaborates:

> Throughout my long experience as a scientist I have heard unfalsiability hurled at so many important ideas that I am inclined to think that no idea can have great merit unless it has drawn this criticism. ... Good scientific methodology is not an abstract set of rules dictated by philosophers. It is conditioned by and, and determined by, the science itself and the scientists who create the science.... Let's not put the cart before the horse. Science is the horse that pulls the cart of philosophy.[75]

The philosophical criteria discussed in the multiverse debate are overwhelmingly those associated with falsifiability and other aspects of Popperian philosophy of science. Now there is no obvious reason for this focus except that a simplistic version of Popper's views seems to be well known among physicists. Why not consider ideas of multiple

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[71] Ellis, Kirchner and Stoeger 2004 (note 39), 928. Of course, the insight that some cosmological problems are inevitably connected with philosophical choices is neither new nor limited to multiverse scenarios. For example, philosophical problems naturally arise from the traditional understanding of the universe as a unique object. See Ellis 2003 (note 55) and literature mentioned therein.

[72] Charles G. Darwin, 'Physical Science and Philosophy', *Nature*, 139 (1937), 1008. Notice that Darwin's advocacy of 'foul means' was restricted to the process of discovery and did not refer to the context of justification.

[73] Barrau 2007 (note 54).

[74] Susskind 2006 (note 31), 196.

[75] L. Susskind and L. Smolin, 'Smolin vs. Susskind: The Anthropic Principle', *Edge* 145 (18 August 2004), http://edge.org/documents/archive/edge145.html.

universes to be a Lakatosian research programme or perhaps a research tradition in the sense of Larry Laudan? If seen in this light, multiverse theory may, like string theory, seem to show some signs of non-empirical progress because of its unifying and explanatory strength.[76]

Many philosophers believe that Popper's criterion for science, even in its more sophisticated versions, bears little resemblance to what working scientists actually do. In fact, empirical studies of science strongly suggest that falsificationism as a research methodology is itself falsified.[77] Colin Howson advocates Bayesianism as an alternative philosophy of science which more realistically and detailedly reflects scientific practise, not least its feature of weighing evidence for and against a theory and to do so by making statistical inferences. With its basis in probabilistic reasoning of degrees of belief, Bayesian methodology corresponds much better to multiverse physics than Popperian falsificationism. Indeed, siding with Tegmark, Susskind, Vilenkin, and others, Howson finds the multiverse to be entirely scientific.[78] Bayesian arguments sometimes turn up in multiverse physics, but it is doubtful if they add support to the cause. A detailed analysis indicates that multiverse hypotheses do not predict the fine-tuning of our universe any better than a single-universe hypothesis.[79]

There are many other philosophies of science than Popper's, and Peircean retroductionism and Bayesianism are only two of them. Admiting that 'most philosophers today consider traditional empiricism to be dead', the eminent philosopher of science Dudley Shapere suggests that some fields of the physical sciences are entering a post-empirical stage. He is ready to take seriously 'the view that physics is in fact approaching, or perhaps has reached, the stage where we can proceed without the need to subject our further theories to empirical test'.[80] In spite of many philosophers' low regard of empiricism, the fact remains that Popperian philosophy completely dominates the discussion among the physicists and indeed among most other scientists. Ever since the 1950s, Popper's views concerning the nature of science have been very influential in astronomy and cosmology, and they continue to be so.[81]

In a recent paper Andrew Yang has analysed the similarly important—and to some extent controversial—role of Popperian philosophy in the biological sciences, including Popper's unfortunate statement of 1974 that Darwinian evolution theory was not a testable scientific theory.[82] Just as in the case of cosmology, Popperian

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[76] Nancy Cartwright and Roman Frigg, 'String Theory under Scrutiny', *Physics World*, 3 September 2007 (online edition).

[77] Sven O. Hansson, 'Falsificationism Falsified', *Foundations of Science*, 11 (2006), 275–86.

[78] Robert Matthews, 'Some Swans Are Grey' *New Scientist*, 198 (10 May 2008), 44–47. A detailed exposition of scientific method from the standpoint of Bayesianism appears in Colin Howson and Peter Urbach, *Scientific Reasoning: The Bayesian Approach* (Chicago, 1993).

[79] V. Palonen, 'Bayesian Considerations on the Multiverse Explanation of Cosmic Fine-Tuning', ArXiv:0802.4013 (2008). See also Earman and Mosterin 1999 (note 23), 34–35.

[80] Dudley Shapere, 'Testability and Empiricism', in *The Reality of the Unobservable* (Dordrecht, 2000), edited by Evandro Agazzi and Massimo Pauri, 153–64, p. 161. Among the examples Shapere refers to, are theories which speak of 'other regions of the universe, or even other universes, which are forever causally unconnected with ours' (p. 153).

[81] The relevance of Popper's philosophy for astronomers and cosmologists is demonstrated in Benjamin Sovacool, 'Falsification and Demarcation in Astronomy and Cosmology', *Bulletin of Science, Technology & Society*, 25 (2005), 53–62. For the significance of the falsifiability criterion during the cosmological controversy in the 1950s, and its use by steady-state cosmologists in particular, see Kragh 1996 (note 11), 244–50.

[82] Andrew Yang, 'Matters of Demarcation: Philosophy, Biology, and the Evolving Fraternity Between Disciplines', *International Studies in the Philosophy of Science*, 22 (2008), 211–25.

standards are often assumed to be authoritative in assessing the scientific status of some fields of biology. And there are biologists who tend to conclude that if their science does not live up to Popper's philosophical views, so much the worse for these views. In a paper of 2005 two biologists advocated that their colleagues in biological research should stop paying attention to the work of philosophers. 'To date, philosophy has been the horse pulling the science cart ... It might be timely to allow science to play the part of the horse pulling the cart of philosophy'.[83] The similarity to Susskind's rhetoric is striking.

It is quite clear that some of the multiverse physicists have no respect at all for philosophers of science in general and for the 'Popperazzi' in particular, to use Susskind's nickname for the modern followers of Popper. 'As for rigid philosophical rules', he writes, 'it would be the height of stupidity to dismiss a possibility [such as the string multiverse] just because it breaks some philosopher's dictum about falsifiability'.[84] On the other side, Smolin and Ellis subscribe to Popperian falsificationist philosophy, if not perhaps in quite the strict sense of Bondi, such as that quoted in section 2.

The demarcation problem has of course been discussed in many other concrete cases apart from the one related to the multiverse, only do most of these involve areas outside established science. One example is scientific creationism and its attempt to be recognized as truly scientific. In the 1986 US Supreme Court case the opponents of creationism—a large part of the US scientific community—came up with a definition of science. They said as follows: 'To be a legitimate scientific "hypothesis" an explanatory principle must be consistent with prior and present observations and must remain subject to continued testing against future observations. An explanatory principle that by its nature cannot be tested is outside the realm of science'.[85] The reader may contemplate if this formula constitutes a problem for the multiverse hypothesis.

8. Conclusions

In this review of the current debate about the multiverse I have called attention to its foundational nature and the attempts to establish a new paradigm for cosmophysics. As I have argued, this is an important issue in current cosmology and one that deserves the attention of philosophers. On the other hand, it would be wrong to believe that this is what occupies the minds of the majority of cosmologists. Ideas of the multiverse presumably have little influence upon the mainstream of observational and theoretical cosmology, which is more concerned with challenges motivated by observation and experiment (such as the nature of dark energy and exotic dark matter). Nonetheless, the debate concerning the multiverse is more than an innocent pastime of a few cosmologists of a speculative inclination.

The community of cosmologists and particle theorists is divided on the question of whether multiverse theories are acceptable science or not, but apparently the

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[83] Kevin G. Helfenbein and Rob DeSalle, 'Falsification and Corroboration: Karl Popper's Influence on Systematics', *Molecular Phylogenetics and Evolution*, 35 (2005), 271–80, p. 279.

[84] Susskind 2006 (note 31), 196.

[85] http://www.talkorigins.org/faqs/edwards-v-aguillard/amicus1.html. The anti-creationism coalition included 72 Nobel laureates (including Steven Weinberg), 17 state academies of science, and seven other scientific organizations.

pro-multiverse and pro-anthropic cause is gaining momentum. Ellis is worried that we are entering an era of 'cosmological myth', with which he means 'an explanatory story or theory that gives means of understanding what happens but remains hypothetical rather than proven'.[86] Other scientists talk of 'post-modern cosmology', where theories are aesthetically motivated, framed in the language of physics but without the possibility of observational or experimental checks.[87] It is not the intention of this paper to judge for or against the multiverse scenario, but merely to discuss and compare the different points of view. I doubt if philosophers of science can justifiably come up with a clear and convincing verdict, and I know that historians of science cannot.

Still, history of science is not unimportant even in such a very recent case. For one thing, arguments from the history of science are sometimes invoked in the debate over the multiverse, if not always in a way that reflects much knowledge of the field. According to Carr, critics of the multiverse are on the wrong side of history:

> Throughout the history of science, the universe has always gotten bigger. We've gone from geocentric to heliocentric to galactocentric. Then in the 1920s there was this huge shift when we realized that our galaxy wasn't the universe. I just see this as one more step in the progression. Every time this expansion has occurred, the more conservative scientists have said, 'This isn't science'. This is the same process repeating itself.[88]

Several advocates of the multiverse have suggested that the traditional or Einsteinian aim of fundamental physics, to explain the world uniquely in terms of first principles, may prove as vain as Kepler's belief in the *Mysterium cosmographicum* that the solar system can be described in exact geometric ratios. Rees, in particular, has drawn parallels between the current situation in cosmophysics and the change in the world picture that occurred between Copernicus and Newton.[89]

Another and more important reason for taking history seriously is that it can be used to put the case of the multiverse it in a broader and more satisfactory perspective. Foundational discussions have happened before and the current one might be just one more, in which case it would be relatively less significant. As pointed out in section 2, there have indeed been precedents, but although these show some similarity to the case they also differ from it. First of all, the alternative approaches to cosmophysics in the 1930s were considered unorthodox and only attracted limited and local support. The discussion was largely limited to a dozen British scientists. The modern arguments for an epistemic change in fundamental physics are certainly controversial, yet they are far from a marginal voice. They are seriously discussed by a fairly large number of physicists, including some of the

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[86] G.F.R. Ellis, 'Cosmology Down the Ages', *Journal for the History of Astronomy*, 39 (2008), 537–38.

[87] Silvio A. Bonometto, 'Modern and Post-Modern Cosmology', in *Historical Developments of Modern Cosmology*, edited by Vicent J. Martínez, Virginia Trimble and Maria J. Pons-Bordería (San Francisco, 2001), 219–36. Post-modern science is related to so-called ironic science, as described in John Horgan, *The End of Science* (New York, 1997), 7, 30–31.

[88] Bernard Carr, as quoted in Tim Folger, 'Science's Alternative to an Intelligent Creator: The Multiverse Teory', *Discover Magazine* (December 2008), online version.

[89] M. Rees, 'Explaining the Universe', in *Explanations: Styles of Explanation in Science*, edited by John Cornwell (Oxford, 2004), 39–66; Livio and Rees 2005 (note 49). See also Frank Wilczek, 'Enlightenment, Knowledge, Ignorance, Temptation', in Carr 2007 (note 26), 43–56.

highest reputation. Concerning the very soul of the physical sciences, the debate is foundational and of interest to the physics community at large.

It is no less interesting from the point of view of philosophy and its interaction with science. Demarcation criteria between science and non-science are traditionally the philosophers' job, but in the current debate they are discussed almost exclusively by the scientists themselves, sometimes inspired by a simplistic Popperian philosophy and little else. The relationship between physics and academic philosophy has never been an easy one, and in the present case more than one physicist have expressed their lack of respect for the opinions of the philosophers. Among the issues I have not dealt with is the relationship between the multiverse and religious belief, a subject which occassionally turns up in the debate, typically in order to demarcate a theory from notions such as natural theology and intelligent design. 'If there is only one universe', Carr says in a recent comment, 'you might have to have a fine-tuner. If you don't want God, you'd better have a multiverse'.[90] I shall not go into this problem except mention that although the multiverse is sometimes considered to be antithetical to divine design—and in effect an argument for atheism—it is perfectly possible to conceive theism and multiverse cosmology to be in harmony.[91]

Let me end by pointing out that the debate concerning the multiverse and the anthropic principle is not limited to exotic branches of cosmology and physics. Potentially it includes also a dimension of research policy. Ellis is expressly worried about the attempts to change the standards of physics, in part because he fears they may have the side effect of making pseudosciences respectable. If funding agencies allocate money to multiverse physics, how can they justify to refuse applications from astrologists? Similar worries were expressed by Dingle in the dispute in the 1930s, when he complained that the fashionable scientific ideas of the period 'are not those which stand in the most rational relation to experience, but those which can don the most impressive garb of pseudo-profundity'.[92]

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[90] Quoted in Folger 2008 (note 88). See also Susskind 2006 (note 31), 380 and Weinberg 2007 (note 57), 39.

[91] Robin Collins, 'The Multiverse Hypothesis: A Theistic Perspective', in Carr 2007 (note 26), 459–80.

[92] H. Dingle, 'Deductive and Inductive Methods in Science. A Reply', *Nature*, 139 (1937), 1011–12, p. 1012.