Helge Kragh

ON THE HISTORY AND PHILOSOPHY OF TWENTIETH-CENTURY COSMOLOGY

1. The Science of the Universe

The term "cosmology" has several different connotations, ranging from a society's world-view to the scientific study of the universe at large. I shall deal only with the latter meaning of the term, but even then it is far from obvious what cosmology is, exactly. We may provisionally define it as the attempt to understand the universe in scientific terms, which in practice means those of the mathematical-physical sciences. The keyword is the domain of cosmology, the universe, and it is this domain which makes cosmology as most peculiar science, for the reason that the universe is a most peculiar entity. It is so basically because it is unique and all-encompassing, features that are not shared by any other domain of science, a point to which I shall return later on. For the moment, let us loosely define the universe as everything in space and time, including spacetime itself, although we should of course restrict this "everything" to what has physical existence and can be subjected to scientific analysis, at least in principle. The universe, rigidly understood as the totality of everything, includes after all phenomena that are beyond the power of physics, such as thoughts and human emotions, and it is obviously not with such things the cosmologist is concerned. He or she is concerned with the structure and composition of the physical universe, that is, the geometrical structure of space and the matter and radiation distributed in it, as well as the temporal evolution of this largest possible physical system. To get a reasonable picture of what cosmology is about, we should add that although, in principle, its domain has no limitations in space and time, in practice cosmology deals only with the large-scale features of the universe, typically of galactic or extra-galactic magnitude: atoms, butterflies, and mountains are all parts of the universe, but they are of no interest to the cosmologist.

The point of mentioning these characteristics of cosmological research is twofold, namely, first to indicate that the "universe" is a difficult and peculiar concept that is widely different from any other scientific domain; and, secondly, to indicate that this understanding of the nature of cosmology is a relatively modern invention which cannot easily be applied to earlier periods.

Before going on to 20th-century cosmology a brief look at the earlier centuries and millenia may be useful, if for nothing else then to increase the confusion. Cosmology is not only a peculiar science because of its subject, but also because of its history, which is not shared by any other science. It is, paradoxically, one of the oldest and one of the youngest of the sciences -- and yet the paradox is easily solved when it is realized that it simply stems from different meanings of the term "cosmology" used at different times. There is, roughly speaking, two kinds of cosmology, of which one is the attempt to make sense of the world at the largest possible scale, and the other is the more limited study of the astronomical environment of the earth, meaning anything from the planets to quasars. The first kind necessarily relies on philosophical reasoning and invites speculation, whereas the other relies on observation and invites mathematical model-making. It is in the first sense that one can claim cosmology to be perhaps the oldest of humankind's proto-scientific activities, for speculations about the structure, creation and meaning of the world are to be found as long back in time as one can trace intellectual history. We still find this kind of all-encompassing cosmological thought in Plato and Aristotle, but from that time onward cosmology changed gradually to become part of astronomy, which basically meant the motions of the planets, including the moon and the sun. As a result of the successes of Hipparch, Eudoxos and Ptolemy, cosmology in the old sense almost vanished from the scientific discourse and was relegated to philosophical and religious discussions. In other words, cosmology became incorporated into astronomy, and since this science dealt with the visible part of the universe, and the solar system in particular, cosmology in the grander sense was not much cultivated. Nor, for that matter, could it be cultivated scientifically, for the observational material was all too limited and uncertain to allow anything but philosophical speculation. It was only after the stars, and then the galaxies, moved to the forefront of astronomical research in the nineteenth century -- and after the spectroscope had given rise to a new astrophysics -- that an observationally based cosmology became a possibility.

The other element in the new cosmology of this century was of course Einstein's general theory of relativity, or, more generally, physical theories of spacetime. It was the fusion of extragalactic observations and the mathematical models based on, or inspired by, the theory of relativity that transformed cosmology from a philosophical subject to something aspiring scientific status. If one wants a date for that transformation, I would say that 1930 is a good choice, for it was then that the expanding universe became a reality through the combined efforts of theoreticians and observational astronomers. The real watershed in cosmology I would uhesitatingly place in 1917, the year that Einstein published his "Kosmologische Betrachtungen" and thereby provided, for the first time, a powerful mathematical theory for the entire universe. What was still missing in this first phase of 20th-century cosmology was physics in the ordinary sense, that is, the physics of matter and radiation: The introduction of nuclear physics into cosmology marked another watershed in the development of the science of the universe, but that only came later, in the 1940s. Since then, cosmology has been guided by three approaches, sometimes in isolation and sometimes in fruitful collaboration, namely astronomical observations, mathematical model-making, and physical theory; to these three elements should perhaps be added a fourth, namely the qualitative philosophical arguments to which I will return in a while. And there may even be added a fifth component, the advance in instrument technology which after all is the basis of all astronomical observation.

Without going in detail one can say that the broad trend since the 1950s has been an increased importance of observations and physical methods, whereas very little progress has taken place in the area of mathematical spacetime models, and the role played by the philosophical element has been steadily decreasing. The models and conceptions of spacetime, which by and large means relativistic models, are of course of crucial importance, but it is remarkable that they all stem from the theory that Einstein produced in 1915 and which a decade later was developed into the Friedmann-Lemaître equations, still the basis of almost all realistic models of the universe.

Given the practically unanimous opinion that Einstein is the true founder of modern cosmology -- an opinion with which I agree -- it may be of interest to ask if the theory of general relativity constituted a revolution in cosmology also in the strong, Kuhnian sense. I shall not try to answer this question here, but want to point out that Einstein's pathbreaking work (as far as cosmology goes) included both revolutionary and evolutionary elements. Those of revolutionary significance are easy to identify, but it may be of some importance to point out that Einstein, in spite of all his novelty, was also a chain in a larger historical process and that he received inspiration from earlier physicists and philosophers; I am thinking not only of Ernst Mach, but also of much earlier inspiration that Einstein acknowledged, such as the correspondence betweeen Newton and Bentley and the Newton-Leibniz dialogue. So Einstein's work was undoubtedly of revolutionary importance, but it also showed the kind of conceptual continuity that we know from other cases of revolutionary science. To speak with Gerald Holton, we may say that although Einstein put cosmology on an entirely new track, the themata of his endeavour can be found much earlier, not only in Newton but as far back as Aristotle's discussion in *De Caelo* concerning the finitude of the universe.

2. Historiographical Topics

It is far from obvious what kind of science cosmology is and, therefore, how it shall be classified in a historical context. As mentioned, there is a long tradition of classifying it as a subfield of astronomy, but although this is reasonable in many ways, it is not an unproblematic classification because cosmology has been considered a somewhat illegitimate child of astronomical research for a very long time. Perhaps it makes as much sense to say that cosmology is a branch of physical science, or an intermediary between physics, astronomy and philosophy; or, which to my mind sounds even more reasonable, to single out cosmology as a science that is relatively autonomous and therefore deserves its own place in the annals of history of science. It is probably this hybrid nature of cosmology, a science that seems to belong everywhere and nowhere in the established classification system, that is responsible for the weak interest which historians of science have shown the area.

And a weak interest is in indeed. It is not too much to claim that modern cosmology is a distinctly underdeveloped part of the history of science, especially if compared with such areas as quantum theory, relativity, solid state physics and particle physics. I suppose that one of the reasons, though not the only one, is that historians of physics do not really count cosmology as belonging to their specialty, that historians of astronomy feel the same way, and that historians of philosophy simply do not have the knowledge and interest necessary to understand the field. It has thus been left, to a high degree, to scientists' and science journalists' more or less amateurish writings, which have very little historical perspective and are clearly objectionable from the point of view of professional history of science. There are valuable and interesting reviews written by astronomers and physicists, but these have more the character of retrospective surveys than proper historical works and fail completely to contextualise the subject. To put it differently, there is no Abraham Pais, Max Jammer or Silvan Schweber among the cosmologists, not even a Jagdish Mehra. Perhaps physical cosmology is too new a field for including this kind of historically perceptive scientist-historians, and if this is the case we have to rely on the historians of modern science to provide a richer, more detailed and more critical account of the development of cosmology than the quasi-history now existing.

At any rate, it is a fact that 20th-century cosmology has only been subjected to historical scrutiny in very few cases, and then mostly for the period before 1940. More comprehensive, scholarly histories that cover also the postwar development are largely limited to two works, which were both published in 1965 and must now be regarded as dated, if still useful. I am referring to John North's *Measure of the Universe* and Jacques Merleau-Ponty's *Cosmologie du XX^eme^ Siècle*, both of which are impressive in their comprehensiveness and philosophical attitude, but which unfortunately were completed just before that magic year of 1965, when the cosmic background radiation was discovered. It is ironical that this is the year often said to mark the rennaissance of cosmology, or the start of physical cosmology, and that North and Merleau-Ponty just missed it and therefore gave accounts which later scientists must find curiously one-sided in their mathematical and philosophical orientations. For good reasons, the big bang models play a minor role only, whereas recent historians would undoubtedly give this area a much more prominent place. The description of the past depends on the present, which is the reason why history is constantly rewritten, and this is nicely exemplified by the mentioned works.

But we live in 1996, more than thirty years after the new cosmology came into existence, and it is certainly time to take another look at the whole development of modern cosmology, a look which will build on the scholarship of North, Merleau-Ponty and others, but also go beyond this and will inevitably be coloured by the events during the last three decades. The problem is only that no-one has done so, and that the history of postwar cosmology is still largely the arena of physicists, astronomers and journalists. This neglect is all the more puzzling because cosmology -- in the older and more restricted sense of the planetary system -- has traditionally ben a central part of the history of the physical sciences. I am thinking of such classics as Duhem's *Systeme du Monde*, Koyré's *From the Closed World to the Infinite Universe* and Kuhn's *The Copernican Revolution*, and all their predecessors. Hundreds or thousands of scholarly works have been devoted to ancient cosmology, to Dante's poetic vision of the medieval cosmos, to Copernicus' revolutionary break with the geocentric system, and to Kepler's attempt to understand the planetary orbits. The result is that we know far more of how the heliocentric system of the "world" came into existence than of the emergence of the big bang idea in modern cosmology. And yet it would be difficult to argue that the 20th-century picture of the evolution of the universe is less of an intellectual achievement, or is less revolutionary, than the picture constructed by Ptolomy, Copernicus and Kepler.

At this point I may mention that there are presently attempts to remedy this situation, and that valuable work has been made in a few areas of postwar astronomy, space-science and cosmology. Thus the history of radioastronomy -- which includes important cosmological applications -- is thoroughly well known thanks to the efforts of Mulkay and Edge, Sullivan, and others, and also the development of X-ray astronomy has been detailed by a few authors. As regards cosmology proper, I have studied the period from 1920 to 1970, and a comprehensive work focusing on the controversy between big bang and steady state models will appear this fall.

The historiography of modern cosmology is faced with all the classical problems that face history of modern science in general. I have already alluded to the problematical relationship between the historian's kind of history and the kind of history written by scientists who have participated in the development. There is a well-known tension between practitioners' historical outlook and the one argued by professional historians, although the gap between the two groups is by no means unbridgeable, such as we know from histories of modern physics and biology. One aspect of the so-called practitioners' history (although not one exclusively to find in such) is the temptation to streamline history, to write it so as it fits with the most modern views and, consequently, ignore the false trails and blind alleys that may seem so irrelevant to the road that led to modern knowledge. I don't need to emphasize that this is bad history, if history at all, and that its main purpose is to celebrate modern science rather than obtain understanding of how science has really developed. Now cosmology is full of those false trails and blind alleys and even today one cannot be absolutely confident that the standard hot big bang model is the final answer, so it is especially important that the development of this field is treated with historical sensitivity and with due respect for the historically important events, whether these fit with modern beliefs or not. In short, we should not be concerned with which models and observations were right or false, as seen from a later perspective, but with what people in the past thought was promising and interesting.

To mention but one example of an anachronistically distorted perspective, very few modern accounts of cosmology give Edward Milne's research programme of the 1930s much attention. If mentioned at all, it is judged to be a rationalistic fancy which led to no real progress and therefore can be safely ignored or ridiculed. Indeed, most modern astronomers and physicists will have a great deal of difficulty of appreciating Milne's non-relativistic, deductive cosmology and may ask why it should be recalled in any detail when it after all turned out to be a failure. But this is precisely where the different perspectives of scientists and historians come in: for the historian there can be no doubt that Milne was a key person in modern cosmology because of his dominating importance during the critical phase of cosmology in the 1930s and 1940s. Instead of focusing on the end-result of his programme, on his reputation after 1950, we should simply stick to the facts of the past, and these show clearly that the agenda within theoretical cosmology during the 1930s was set by Milne and those who followed him.

There is a related danger, also known from other branches of history of science, and that is the temptation to trace history backwards in time in order to find precursors of those ideas which today are recognized to be fundamental in cosmology. One such idea is the notion of the big bang, and because of the prominent role played by this idea in modern cosmology it is tempting to think that it also played a prominent role in prewar cosmology. But one should be very cautious and keep to reading the texts in their historical contexts and not with an eye on later knowledge. For example, it has been claimed that the big bang concept was discussed by the philosopher Henri Bergson as early as 19xx, before Georges Lemaître gave voice to the idea in 1932 and developed it scientifically. Not only is this claim misplaced -- one could as well claim that the originator of the big bang idea was Moses, or whoever wrote the Genesis of the Old Testament -- it is also a claim which was made only because the big bang became an interesting notion many years later, and it is a claim that doesn't explain anything or make us understand the history of cosmology any better.

Let me mention one more example of a rather different type, namely the important universe model proposed in 1932 by Einstein and de Sitter, describing a universe with zero pressure, zero space-curvature, and zero cosmological constant. As is well known, the Einstein-de Sitter universe is continuously expanding, corresponding to the distances between galaxies varying as the time in the power of 2/3, or, put differently, with an age of the universe equalling 2/3 of the Hubble time. The Einstein-de Sitter model is a typical big bang model, with a zero radius at the beginning of time and then following a monotonous expansion, and because of its simplicity it often figures in modern discussions of cosmology as a big bang exemplar. And yet it would be misleading to believe that either Einstein or de Sitter presented their model as a big bang theory in 1932. When we look at what is actually in that paper, instead of interpreting it in accordance with later knowledge, we realize that the authors have nothing to say at all about the big bang features and that they do not even state the variation of distance with time. A historically correct view of the Einstein-de Sitter universe anno 1932 is obtained by reading what is in the paper and analyzing the text within the context of the early 1930s, and not by rationalizing what might have been in it or was implicitly in it.

Before leaving the historical part of my paper I want to point out that what little there has been written has almost been completely devoted to either cosmology's scientific aspects or its philosophical implications. This emphasis on the scientific and intellectual aspects is perhaps reasonable enough, but it shouldn't make us forget that it is only one approach among many and that there are other, valuable approaches which until now have scarcely been investigated at all. Think about solid-state physics or particle physics, for example. The development of these fields have been dealt with not only from a scientific point of view but also from broader, social and institutional points of view, and that with the result that we know a great deal about the history of these disciplines and the interaction between intellectual and social factors. How different with cosmology! We are sorely in need of research in these non-scientific aspects, which includes such questions such as funding, public appeal and responses, disciplinary interactions and tensions, education and training, the geography of cosmological research, and networks and school-building in cosmology.

3. Philosophy of and in Cosmology

Cosmology has its philosophical appeal in common with quantum mechanics, but in a rather more direct and fundamental manner: cosmology *is* in part philosophical, and the great questions concerning the origin and structure of the world (not to mention its end) has always been an integrated part of cosmological thought. So whereas one can easily deal with the history of quantum theory without entering philosophical topics, this is hardly possible in the history of cosmology.

It will be useful to distinguish between two kinds of philosophy related to cosmology, one which can be called philosophy *of* cosmology and another philosophy *in* cosmology. The first kind consists of philosophical analysis of an existing scientific field, its subject-matter, methods and possibilities of obtaining true knowledge, and is typically the work of professional philosophers of science. Philosophy in cosmology, on the other hand, is the kind of spontaneous philosophical considerations that enter cosmology as a living scientific field and which is part of the history of that field; it may deal with many of the same questions as those of philosophy of cosmology, but it intervenes directly in the scientific discourse and is often the work of the scientists themselves, although philosophers may also have a word in the process. This distinction is known also from some other areas of science, for example in early quantum mechanics where Heisenberg, Bohr and others used philosophical arguments in their attempts to understand the new theory, whereas philosophers' interest in the theory came somewhat later and played very little role in the scientific process. Compared with quantum mechanics the situation in cosmology is, roughly speaking, that philosophy in science played a greater role in cosmology whereas philosophers of science has only been insignificantly interested in the questions of cosmology.

One of the classical philosophical problems is simply whether the concept of the universe has any physical meaning or if it is just an idea, and this problem obviously depends on another one, namely, what is to be understood by the "universe." I started by mentioning that "universe" normally means the totality of physical things, but many scientists would add a further clause, namely, that these things have to be causally connected; since cosmologists happen to be situated on earth, this means that the universe, according to this view, is that part of spacetime and its physical constituents that are accessible in principle to observers on earth. This is an empirically reasonable definition which limits the universe to a spatial radius of the order of cT, or about 10 billion light years, but it is clearly a definition that ignores the multitude of things outside this radius. According to most cosmological models there is a cosmic horizon outside which galaxies recede from us with velocities larger than that of light, and which are therefore unobservable even in principle. Yet these objects too belong to our universe, in the wider sense, and we therefore have to accept that cosmology deals with objects that are unobservable in principle, which of course is a philosophically controversial claim, especially to empiricists.

Cosmological knowledge seems to be conditioned by principles or assumptions that are themselves completely unverifiable insofar as they can only have a limited inductive support. The most important of these assumptions is the Cosmological Principle which includes the postulates of spatial homogeneity and isotropy and which lies at the heart of all models satisfying a Robertson-Walker metric. This principle, together with the relativistic field equations, determines models of the complete universe, which is a satisfying feature, but it also makes rough predictions about regions of the universe which are beyond observation. These predictions or knowledge-claims are postulates that can never be verified and so their reliability must remain a matter a faith. They are consequences of the Cosmological Principle, but this principle can only be verified in the observable part of the universe and its extrapolation beyond this part rests on faith, not knowledge. Still, there are different kinds of faith, and to say that a claim is a matter of faith does not imply that it is either irrational or completely arbitrary.

If the universe is the totality of things, then, as a consequence, it is also unique: there exists only one universe, not because we have empirical evidence for it, but because the concept of the universe is defined as it is. Yet many physicists speak of this or that universe, or about many universes, as though a universe was the same kind of object as an electron or a bottle of wine. In some cases such parlor is innocent: when the scientists speak of "universes" they often really mean "models of the universe," and there are obviously many cosmological models seeking to describe the one and only universe. However, in other cases physicists refer to the idea of multiple universes, either so-called bubble-universes or other theories involving causally isolated regions of spacetime. The idea of multiple universes has its own philosophical problems, but I just want to mention that the way in which scientists use the term "universe" is often loose and confusing: There is nothing wrong with theories of multiple universes, but if one insists on calling such spacetime-regions "universes" one should invent a new word for the totality of things, which is the ultimate domain of cosmology.

In any case, whether adopting the wider or more narrow point of view, from an empirical point of view the universe is unique. There is only one universe about which we can have empirical knowledge, and this, as I said, makes the domain of cosmology different in principle from other domains of science. To speak philosophically, science is *nomological*, meaning that it normally deals with objects or events which can be generalized or repeated and in this way be subjected to explanations by law; but there is only one universe, the big bang is a non-repeatable event, and it makes no sense to generalize cosmological knowledge which is supposed to be valid for the entire universe. In other words, cosmology seems to be non-nomological and therefore, according to some scientists, in need of its own methods of inquiry. This kind of philosophical argument was for example discussed by Hermann Bondi in the 1960s, when he argued that there are no, and can be none, cosmological laws and neither can the most general features of the universe be explained. For to explain something amounts to demonstrating that it is a special instance of some general class, and there is no general class of universes, and for this reason Bondi argued that all that cosmology can possibly do is to describe or record the universe.

I just mention this as an example of how philosophical reasoning may enter cosmology and I would like briefly to mention another example from the same period. The basic epistemological question in cosmology is if it is possible to have reliable knowledge af the universe. In other words, why should we believe that the cosmologists' mathematical models represent the real universe, most of which is forever hidden from us? There have been periods of optimism and pessimism in the more recent history of cosmology, and in the years about 1960 it seemed to some cosmologists that pessimism was warranted by the incapability to decide observationally between the big bang and steady state models. William McCrea, a leading British cosmologist, argued that even in principle we cannot predict the behaviour of a remote part of the universe and that, the farther away the region, the less precise will our predictions be. He formulated a cosmological uncertainty principle of the same fundamental nature as the one known from quantum mechanics, namely, that there will be an uncertainty in cosmological knowledge proportional to the redshift, which meant that it would be meaningless to try distinguishing between cosmological models which only differ at very large distances. If the universe is fundamentally unpredictable and unexplainable it would seem that cosmology is not really a science, and this was indeed the conclusion drawn by McCrea and some other prominent cosmologists of the period.

The same period witnessed an interesting discussion between astronomers, physicists and philosophers concerning the scientific status of cosmology and, more specifically, which of the two competing world-models was the most scientific one, that is, preferable on methodological grounds. This is a topic I have dealt with in detail in my forthcoming book, and today I shall merely point out that such a question obviously must rely on some methodological demarcation criterion, that is, on a philosophical and not a scientific principle. It was generally agreed that some degree of testability is a minimum requirement for a theory being scientific, and the steady state theoreticians emphasized in particular Popper's idea of falsifiability as the overriding methodological criterion. Indeed, the steady state model is a prime example of a Popperian theory because it yielded precise predictions and in this sense was eminently falsifiable. From a methodological point of view the rival big bang theory was much more of a mess and didn't live up to Popper's standards of a good scientific theory. The fact that it turned out that this methodologically unsatisfactory theory was nonetheless a better and truer theory than the steady state theory invites two comments. The one is that man-made methodological criteria can never decide which theory is true, and which false, but only be recommendations of how to secure progress in science; a methodologically ugly theory may well turn out to be correct, as it happened with the big bang theory in the mid-1960s. Well, it has later been improved and today it is not as ugly as it was. The other comment is that the controversy between the two world-models in no way contradicts Popperian falsifiability; Popper emphasized the vulnerability of theories as a positive feature, not because such theories are likely to be correct, but because their refutation represents knowledge of what is not the case and thereby makes it easier to find a better theory. It was in this way, by being refuted, that the steady state model played an important role in the progress of cosmology.

There are many more interesting philosophical problems in cosmology, such as the questions of the anthropic principle and the problem of creation in big bang theory. These have been much discussed during the last couple of decades, both by philosophers and cosmologists, but -- as one would rather expect -- without any satisfactory solution. As far as the anthropic principle is concerned there seems to be a growing consensus that this is not, after all, a scientific meta-principle of any real worth. And in spite of much discussion and many ingenious suggestions, the ultimate question of the creation of the universe seems as far from a solution as ever. But time does not allow me to go into these problems and I will leave the matter with these loose remarks and go on to another philosophical problem related to modern astrophysics.

4. The Epistemic Status of Cosmological Objects

But time forces me to be selective and I would like instead to end with discussing a suggestion made by the Canadian philosopher Ian Hacking, who is known in particular from his book *Representing and Intervening*, where he argues for entity realism when we are able to manipulate and make tools of theoretical entities; for example, we have reason to believe that electrons really do exist because we can use electrons in a variety of ways, make them behave as we want, and manipulate them in experiments. That sounds fine enough, should one doubt that electrons exist, but Hacking places so much emphasis on experiment that he is unwilling to accept that some astrophysical quantities, such as quasars and black holes, can be granted the same ontological status as electrons. In fact, with regard to distant and exotic astronomical objects he argues for what he calls a "modest anti-realism," that is, that we can never have knowledge of their existence. Hacking argues that extra-galactic astronomy is not a real science, because the hallmark of science is active experimentation and interference wih objects, whereas astronomical objects are non-manipulable and can only be observed, not experimented with; for this reason he believes that astronomy and astrophysics consist in model-making and must necessarily do so, and that astronomical knowledge is therefore less reliable and of a different kind than knowledge obtained from laboratory science.

Although he does not mention cosmology, it follows that if we have reason to doubt the knowledge claims about quasars, black holes and gravitational lensing, then we have even more reason to doubt cosmological knowledge, for the universe is surely not an "object" which can be scrutinized in the laboratory. By thus picturing astronomy and cosmology as areas between speculation and science, Hacking indirectly follows the pessimistic tradition of McCrea and others. Incidentally, the suspicion that astrophysics is not a proper science goes much farther back in time and was espoused by Auguste Comte in his *Cours de Philosophie Positive* in the 1830s, when the French philosopher claimed that we could never have positive knowledge about the sun or the stars. Well, Comte turned out to be seriously wrong, and I would say that Hacking's philosophically based contemporary doubts are not much better. They have been severely criticized by the American philosopher Dudley Shapere, and I shall only mention a few reasons why skepticism or anti-realism about astrophysical objects is unwarranted.

The main problem seems to be Hacking's claim that secure knowledge is limited to those objects that can be reproduced or interfered with in laboratory experiments. Of course one cannot experiment with a quasar, and even less with the universe, but this is not an unusual situation in science and doesn't give ground for anti-realism. This is in fact a situation shared by all those sciences which deal with the past, which not only include astronomy but also palaeozoology and a good deal of geology; we cannot experiment with the past, but this doesn't mean that it is inaccessible to us, only that we cannot interfere directly with it and have to rely on those traces from the past that happen to survive today. Because we cannot experiment with the past, we have to interpret the traces in accordance with some assumptions such as a principle of uniformitarianism, which in the case of physics implies that the laws of nature were the same in the past as they are today. It is in this way that we have gained reliable knowledge about dinosaurs and the formation of rocks, and there is no difference in principle between knowledge about the past of the earth and knowledge about distant astronomical objects. The traces from astrophysical objects arrive to us on earth in the form of signals, usually electromagnetic waves, and then they can be analyzed in the laboratory. To picture modern astronomy and cosmology as simply mathematical model-making in the style of Ptolemy or Copernicus is to give a highly distorted picture and ignore the vast amount of experimental work which is routinely done in modern astrophysics.

As far as cosmology is concerned, Hacking's anti-realism might have been reasonable in the 1950s and early 1960s, but it just doesn't fit with the later development and in particular not with the famous discovery of the cosmic background radiation in 1965. This radiation came from the universe and was detected on earth, not produced in the laboratory, and all what astronomers could do was to try measuring the radiation; because it was observation rather than experiment Hacking would perhaps not be willing to admit it as convincing evidence of the big bang, but the existence of an isotropic, blackbody-distributed microwave radiation can surely not be doubted. Although we cannot manipulate with the radiation, but just have to accept it as it is, we can *use* it to obtain knowledge, to make predictions, and to correlate theoretical knowledge; so the radiation from the heavens is far from a passive signal, it functions as a tool and since it has proven a very useful tool there is all reason to admit that it was caused by a real event, most likely the decoupling between matter and radiation in the early history of our universe.

To make a long story short, there are all kinds of problems in cosmology, some philosophical and some scientific, but this is hardly surprising in regard of the wildly ambitious aims of this science. Scientific cosmology is less than 100 years old and the remarkable thing is not that there are so many problems, but that we have some reliable knowledge of the universe at all and that progress does take place also in cosmology. Moreover, this knowledge has been acquired not by using some special kind of reasoning, but essentially by following established rules of scientific inference, including a heavy dose of nuclear and subnuclear physics. The fact is not only that we can have knowledge about the universe, but that we do have such knowledge; of course this knowledge is highly incomplete, but what else could be expected from a science with the entire universe as its domain?

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