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Cosmology after Half a Century

Fifty years after Einstein's paper of 1917 cosmology is in a supremely interesting state.

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The modern study of cosmology is now 50 years old. After probably the most checkered history of any branch of natural knowledge, all the main predictions of big-bang cosmology appear to have been almost suddenly found to be fulfilled. Counts of radio galaxies have been taken so far back in time, it is claimed, that there are no more to be counted; the predicted cosmic background radiation has been discovered; the helium problem seems to have been resolved in harmony with the properties of the background radiation; the universe is found to be isotropic and homogeneous, as the simplest big-bang models suppose; the constants of physics are found to be as universal and as invariable as these models require; the detailed study of such models with the aid of large-scale computing seems to be making it possible to fit some one model to the optical and radio observations.

Let us briefly recall the history leading to this apparently happy state. If substantiated, the big-bang model must rank as one of the very great achievements of science. Because of the vagarious history of the subject, however, I am bound to proceed to some critical assessment of the situation. On the empirical side, this model is vulnerable to a variety of tests of which the outcome is not yet known. Were it found that large red shifts are produced in more than one way, as recently suggested (*1*), or that some means (maybe red shift or apparent size) of measuring "distances" of radio galaxies shows a distribution in depth different from that inferred from radio fluxes, or other methods, then the whole subject would be back in the melting pot. On the epistemological side, the proposed sort of model raises difficult questions about the transfer of information in the cosmos and about the status of the laws of physics in cosmology. Also, there is obviously much that is left out of the model—the problem of matter and antimatter, the problem of the formation of galaxies and clusters of galaxies, and other factors.

The way that has led to the currently considered model is probably the only path open at the present time. Whatever happens, considerations of the sort mentioned below will have to be pursued. But until the empirical situation has become more certain—and we must hope it soon will do so—there seems to be no clear clue as to the route that further developments will take.

Brief History

The modern phase in the study of cosmology began with the publication of Einstein's paper of 1917 in which he presented his famous original static model universe (*2*). He derived it from his theory of general relativity with a nonzero cosmological constant Λ. The model possessed remarkable qualitative features, even though it made no quantitative predictions that could be tested by available astronomical observations. It showed that general relativity was able self-consistently to treat a "whole universe"; it yielded a unique universe (subject to certain general and apparently inevitable requirements); this universe conformed in a general way to Mach's principle (sine Λ was related to the mean density of the universe so that, as Mach required, local properties depended upon the actual material contents of the universe in the large). At the time, a theory that did any one of these things would have been regarded as a great achievement. To do them all at once seemed to be an overwhelming vindication of general relativity.

A few months later de Sitter's (*3*) discovery of his model universe shattered Einstein's satisfaction even more than it need have done. De Sitter used the same theory as Einstein and imposed apparently the same general conditions, but he obtained a different model. In the first place, therefore, by seeming to show that it admitted more than one universe, de Sitter enormously diminished the status of Einstein's theory. Furthermore, de Sitter's model was empty; since it had a well-determined behavior but no material content, it seemed to be as far as could be imagined from satisfying Mach's principle.

One reason why de Sitter's model was a less serious threat to Einstein's position than at first appeared to be the case was that Einstein demanded a static model (as was thought necessary at the time), and de Sitter's model was not properly to be regarded as static. It could be given an apparently static form only as a result of a mathematical accident. Another reason was that in general relativity there is no distinction between space-time and the material contents of space-time. The whole constitutes a "field," and whether the field is Machian or not requires much more sophisticated discussion than had been attempted (*4*).

So long as astronomers kept to the idea that the universe as a whole has to be static, Einstein's model was the only known theoretical model satisfy-

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ing this requirement. What de Sitter had discovered was about the simplest possible model of an expanding universe. For in it any test-particle is subject only to cosmical repulsion away from the observer and to no gravitational attraction. De Sitter expected that his model would be found to be a limiting case of a more general model. A dozen years later, Eddington (*5*) pointed out that Einstein's model is unstable and, if it is disturbed in the sense of a small initial expansion, it will go on expanding and will tend to de Sitter's model as time increases. So the irony of this whole business is that the Einstein model and the de Sitter model have to be regarded as essentially the same model! This is how Eddington continued to view the matter and almost how Lemaître came to view it.

Meantime, Friedman (1922) and Lemaître (1927) had discovered nonstatic universes as such. In due course, this caused Einstein to discard the "cosmical terms," that is, to put $\Lambda = 0$.

There then came for the first time the opportunity to compare theoretical model universes with actual quantitative observations of the astronomical universe on a larger scale than had ever been contemplated before. For, in 1929, Hubble published his discovery of the apparent recession of the nebulae in accordance with what is now called Hubble's law. This revealed what appeared to be a concerted behavior of the universe as a whole; nothing like it had been known before. It had, however, been predicted by relativity theory (through the work of de Sitter, Friedman, and Lemaître). So it was hailed as a triumph of that theory far more than was Einstein's original derivation of the first cosmological model.

It soon became evident, however, that quantitatively the position was not nearly so good. In particular, every relativistic model that was applied to interpret the observations gave an effective age of the universe less than 2×10^9 years. This was much less than the age of even the oldest rocks on Earth.

Such difficulties remained insuperable up to 1948. In that year, Bondi and Gold, and, independently, Hoyle advanced the hypothesis of continual creation and of steady-state cosmology (*6*). The concepts involved went much further than an attempt merely to resolve the age difficulty. But it was this difficulty that impelled people to look for an alternative to relativistic cosmology, and that made them willing to contemplate a revolutionary remedy.

Certain general features of steady-state cosmology have to be recalled. (i) It is the obvious and only simple alternative to relativistic cosmology; this can be seen as follows. Astronomers see a universe consisting of material in process of dispersing (always provided the usual interpretation of the red shift is correct). Were they to observe again at a different epoch they would obviously not see the same material in the same state. The simplest alternatives are that, at two different epochs, astronomers would see the same material or they would see the same behavior. These alternatives lead to relativistic cosmology and to steady-state cosmology, respectively. (ii) The simple steady-state model was unique. On conceptual grounds this was again a high recommendation. On observational grounds, it rendered the model as vulnerable as possible to observational test. (iii) With regard to age, what had previously been the calculated age of the universe now became (to within a factor of the order of unity) the mean age of the contents of any large region of the universe.

Cosmologists thus had a theory that had considerable conceptual appeal, that avoided the age dilemma, and that was exposed to observational test. Since it was the only alternative to evolutionary cosmology, and since it possessed this vulnerability to testing, it was natural and proper for astronomers to direct their efforts to trying to find some feature of the actual universe that was incompatible with the model. As was repeatedly emphasized, any one such feature would necessitate the rejection of steady-state cosmology. In practice, it entailed discovering, if possible, some intrinsic property of the universe that is not the same at all distances.

In the years after the emergence of steady-state cosmology, radio astronomers showed that they could observe the universe in the large, and, indeed, they could do so out to greater distances than existing optical telescopes could reach. They joined with optical astronomers in the assault on steady-state cosmology.

As time went on, a number of observations that were at first claimed to contradict steady-state cosmology were subsequently shown to be mistaken or misinterpreted. So it became increasingly difficult to convince adherents of steady-state cosmology that any further observations genuinely violated the theory. Thus until about 1966 there were still cosmologists who held that no observation was definitely in conflict with the theory. As a matter of history, the position then changed almost overnight.

Naive Cosmology

By this we shall mean the simplest sort of big-bang cosmology interpreted quite literally. Thus the universe is supposed to have started from a singular state at cosmic epoch $t = 0$. It then expanded at speeds calculated in accordance with relativistic cosmology. At a certain early stage, element-formation occurred, particularly the formation of helium. This resulted in the existing nuclear abundances except insofar as these have been modified (by calculable amounts) by nuclear reactions in stars. At a further early stage, the universe as a whole became optically thin; radiation existing at this stage must survive, subject to the appropriate red shift, as cosmic blackbody background radiation. At some later epoch, the formation of galaxies and clusters of galaxies took place. The whole of this evolution is supposed to have proceeded from the outset in strict accordance with the laws of physics as we know them (or as we can discover them at our epoch) (*7*).

All this does not determine a priori a unique model. But it is assumed that comparison with observation will determine values for the three well-known parameters H_0, q_0, σ_0, ($H_0 =$ Hubble's "constant," $q_0 =$ deceleration parameter, $\sigma_0 =$ density parameter). This is equivalent to selecting a particular one from the two-parameter set of Friedman's models and ascertaining the cosmic epoch t_0 at which we make our observations. The situation may be claimed to be that resulting from a perfectly straightforward application of general relativity to the cosmological problem, unclouded by any philosophical questioning or by any tampering with the theory so as to accommodate, for example, continual creation.

Observational Support

I summarize the observational evidence as it may be cited in support of this simple view—we shall later reexamine it more critically.

Age. It is now known that the age difficulty was due mainly to a mistake in evaluating the zero point of the period luminosity relation for classical cepheids. When Baade put this right in 1952, and others extended his work, it could no longer be definitely claimed that a real age difficulty exists.

Radio counts (earlier). The earlier Cambridge (England) and Australian counts of radio sources showed that there is very considerable evolution in the universe in the large.

Radio counts (latest). The latest Cambridge counts appear to extend so far back in time that they reach the epoch at which galaxies (or, at any rate, radio galaxies) were only coming into existence. It is now claimed that a radio telescope capable of seeing farther into space, and so farther back in time, would not show significantly more sources than the instruments now in use (*8*).

Helium. The cosmical abundance of helium is well accounted for by the theory. The very recently redetermined lifetime of the neutron, insofar as it affects the result, appears to do so in the direction of improving the agreement with observation (*9*).

Background radiation. The discovery in 1965 of the microwave background radiation (the so-called 3°K radiation) was a striking vindication of the theory. It fits well with the helium calculation. It was this, more than anything else, that produced the change mentioned above.

Physical constants. Various recent investigations are interpreted as showing that the constants of physics are the same throughout the observable universe (*10*). This supports the hypothesis that the universe obeys the same physical laws throughout.

Thus in the last year or two everything possible seems quite suddenly to have fitted almost perfectly with the simplest possible interpretation supplied by naive cosmology. If the situation can be accepted it means that cosmology has rapidly gone from explaining almost nothing to explaining an enormous amount about the observed universe.

Discussion

It may be that the universe in the large is as simple as the naive treatment supposes, and that astronomers have already discovered its main features. However, this seems too good to be true! I started with a brief history because this teaches us from past experience to look at the position as critically as possible.

Empirical difficulties. There are difficulties about the interpretation of the red shift (*1*). At present, not many cosmologists positively accept the suggestion that a large part of the red shift might be other than "cosmological." But quite a number do recognize that there is still a problem. Naive cosmology accepts, of course, only the simplest cosmological interpretation.

Very recently, the whole position in regard to the counts of radio sources has been put back into the melting pot by the new observations made by J. G. Bolton and his colleagues in Australia (*11*). Their work seems to show that the results of such counts depend in an unexpected and unexplained manner upon the radio frequency at which the observations are made. If so, the interpretation of the counts is still altogether obscure.

If the theory asserts that the original formation of helium produced a helium abundance of, say, 25 percent by mass, then any large body of matter in the presently observed universe would be expected to contain at least 25 percent helium. If any such body is found with significantly less than this amount (at any rate if the helium is deficient relative to hydrogen), this would contradict the theory. As is well known, a few stars have been found that appear to contain very little helium; if their helium deficiency is confirmed, the theory will be in grave difficulties.

The observation of the microwave background radiation is an extremely difficult one. Even if the existence of the radiation is accepted, as it generally is by the observers concerned, it is still not established observationally that it is blackbody radiation. If it is not, its significance would not be at all the same (*12*).

At present it is not known whether the luminous galaxies comprise most of the matter in the cosmos, or whether there is a comparable, or even greater, amount in the form of diffuse intergalactic material. Various lines of observation seem currently to be on the verge of providing significant bounds to the density and temperature of such material. Also, we are learning to ask whether there are, say, "x-ray galaxies" or "infrared galaxies," and also whether the universe is pervaded by a great ocean of neutrinos. Until such empirical questions are settled, no cosmological theory can be well established.

Supposing, however, that the universe does behave like a Friedman model, it is possible in principle to evaluate the parameters H_0, q_0, σ_0 from various sets of observations. Considerable effort is being directed to this end. But it is certainly not yet known whether there is one set of values that is consistent with all the sets of observations.

In this connection, we know that $\Lambda = 0$ if and only if $q_0 = \sigma_0$, and recent empirical determinations of q_0, σ_0 mostly do not satisfy this condition. So we seem to be again faced with the problem of interpreting a nonzero cosmical constant which Einstein long ago showed to be so difficult.

In practice there are more parameters than H_0, q_0, σ_0 to be considered. For, in connection with each particular set of statistics, allowance has to be made for evolutionary effects that may influence them. It is only in the simple, steady-state model that these effects are absent and that was why, at any earlier stage in the subject, effort was concentrated upon testing the steady-state model. The time has now arrived, however, when naive cosmology must meet the challenge to produce a single self-consistent model that quantitatively reproduces all the observed properties of the universe in the large.

Conceptual Difficulties

The naive view implies that the universe suddenly came into existence and found a complete system of physical laws waiting to be obeyed. Less crudely, according to this view, the notion that a changing universe should change in accordance with unchanging laws is regarded as acceptable. Actually, it seems more natural to suppose that the physical universe and the laws of physics are interdependent. This leads us to expect that, if the universe changes in the large, then its laws might also change in a way that could not be predicted; a change in a predictable manner would be a logical contradiction. Again the naive treatment of physical laws leads to the concept of the unique universe of experience being one amongst any number of other possible universes that might have existed in conformity with the laws. It seems impossible to assign significance to this concept as it stands.

The naive treatment of the homogeneity of the universe also presents a profound conceptual difficulty in regard to the transfer of information in the universe. The postulated homogeneity means that any two parts of the universe behave in the same way at the same cosmic epoch. But they cannot, of course, exchange information at that epoch.

If we see a part of the universe, say 10^{10} light years away, then the homogeneity implies that our part of the universe must behave now in the way in which the other part is destined to behave 10^{10} years after we have received any information from it. This is an aspect of a problem that I have discussed from somewhat different standpoints elsewhere (*13*). The point is that, whereas the model is taken to be homogeneous for the sake of simplicity, if the actual universe is found to be homogeneous this is a feature for which some physical explanation must be found, and this is not easy.

It is worth remarking that a similar difficulty is not necessarily concerned in Hubble's law. So long as we may suppose that the observed contents of the universe were in the past a lot more congested than they are now, and that their speeds have not greatly changed since then, they are bound to exhibit a "Hubble behavior." Under such circumstances, if we see a galaxy at distance d we do so only because it is receding from us with speed d/t, where t is the time since maximum congestion occurred. Then the speed of recession is proportional to the distance and, in particular, this behavior exhibits complete isotropy. Hubble's law is therefore not a manifestation of any *concerted* behavior of the universe.

Finally, the naive theory provides no answer to certain deep problems of physics that must certainly be bound up with cosmology. In 1873 J. C. Maxwell (*14*) wrote, "In the heavens we discover by their light . . . stars so distant that no material thing can ever have passed from one to another; and yet this light . . . tells us also that each of them is built up of molecules of the same kinds that we find on earth. . . .

"No theory of evolution can be formed to account for the similarity of the molecules . . . . On the other hand, the exact equality of each molecule to all others of the same kind gives it . . . the essential character of a manufactured article and precludes the idea of its being eternal and self-existent."

Here "molecule" is used in the old-fashioned sense to include molecule, atom, ion. . . . Actually it is now almost certain that the most energetic cosmic-ray particles come from remote galaxies so that we can directly compare matter from different galaxies. So far as we know, the result is still the same as Maxwell inferred: all electrons are everywhere the same, all protons are the same, and so on. We should expect a sufficiently sophisticated theory to tell us why this is so.

The other big problem in this category, which must be closely related to the one just stated, is that of matter and antimatter. If indeed the observed universe consists almost entirely of matter, rather than of comparable amounts of matter and antimatter, we should expect cosmological theory to account for this asymmetry. On the other hand, if there are comparable amounts of both sorts, some galaxies must be made of one sort and some of the other sort. Cosmology should then tell us how the segregation occurred.

Attitudes and Interpretations

The pragmatic attitude is to allow the naive model to supply the form of a set of relations between various observable properties of the universe. With empirically determined parameters, these relations are taken to summarize our knowledge of the large scale behavior of the observed universe. We do not take the theory that gave us these relations too literally. In the light of the discussion above a more satisfying theory must be sought. Nevertheless, any new theory is expected to yield about the same observable relations as the simple theory insofar as they deal with the same phenomena and insofar as present observations are substantiated. Naturally, it is assumed that astronomers will continue to work to clear up the empirical difficulties that we have mentioned—if the history of the subject has taught nothing else, at least it should have prepared the way for continual observational surprises.

With regard to queries about the status of the laws of physics, each of at least three different attitudes seems to be logically justifiable. (i) The laws of physics as usually interpreted are certainly satisfactory for dealing with our locality in space and time. Since no other way is known, when larger and larger regions are considered, we can only see how far we can get by using the same laws. If there is some sense in which the whole universe can be dealt with, then, as it is approached, our usual treatment should be expected to become less applicable. There is reason to expect to be able not to predict but only to describe the behavior of the whole unique universe. (ii) On the other hand, if when regions of greater and greater extent are considered there is no indication that our treatment becomes less applicable, it should be inferred that we get no nearer to treating the whole universe. In that case the notion of the whole universe and of its uniqueness would lose any simple meaning. Instead, we should have the notion that our presently observed universe is in some way part of something larger, in which other possibilities are realized. (iii) The laws of physics may be more like mathematical theorems than, for instance, the "laws" of a human community. The laws of a community come into existence with the community, and they change as the community changes. Mathematical theorems do not depend upon the entities that "obey" them. This was effectively the way in which Eddington and Milne, taking different approaches, came to regard the laws of physics. If the laws have this mathematical character, then presumably they do not change as the universe changes. Again we might reverse the argument and infer that the laws must have this character if sensible results are achieved when physical laws are applied to a changing universe. It is easier to accept this view in terms of a relativistic four-dimensional model universe than in terms of an observer collecting information and trying to use it to predict his future experience. I have indicated elsewhere (*13*) the limitations of the latter procedures and I do not see that they can be evaded by the making of models.

Turning to the question of the creation of matter, the reason why the big-bang and the steady-state cosmologies are, as I have said, the simplest possibilities to contemplate is that they are extreme limiting cases in this regard. In the big-bang, creation is as concentrated as possible in space and time; all matter is created once and for all in one uncaused event. In the steady-state, creation is as dispersed as possible in space and time; every elementary particle (or maybe every hydrogen atom) is created in its own uncaused event and such events are distributed uniformly in space-time. Apparently, the fact that observation contradicts the simple steady-state model must be accepted. But this is not a good reason for going to the opposite extreme. It would be natural to consider the possibility of continual creation that is not necessarily uniform in space-time. However, I have suggested (*15*) that it is preferable to consider the hypothesis of an interaction in existing matter in which matter is not strictly conserved. This removes the question of creation from the discussion. The hypothesis leads to the concept of a self-propagating universe, which gives some hope of accounting for the identity of elementary particles of any one species, and of dealing with the problem of matter and antimatter (*15*). Further, since the resulting universe would reproduce itself without the assistance of a genetic code, the universe would forget what it was like after a few generations. So it would not be possible to make predictions over more than that time or the corresponding distance, and this fits in with the limitations upon prediction mentioned in the preceding paragraph. Hoyle and Narlikar (*16*) have given a more sophisticated treatment of the nonconservation of baryon number.

Finally, there is the question as to how the homogeneity of the universe is brought about. Observation reveals a high degree of homogeneity and, as I have said, this signifies some physical coherence in the universe. The idea of a self-propagating universe may help; so also may the existence of a neutrino background. These considerations result in the situation described in the opening section of this article.

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Flash Photolysis and Some of Its Applications

George Porter

One of the principal activities of man as scientist and technologist has been the extension of the very limited senses with which he is endowed so as to enable him to observe phenomena with dimensions very different from those he can normally experience. In the realm of the very small, microscopes and microbalances have permitted him to observe things which have smaller extension or mass than he can see or feel. In the dimension of time, without the aid of special techniques, he is limited in his perception to times between about one twentieth of a second (the response time of the eye) and about 2×10^9 seconds (his lifetime). Yet most of the fundamental processes and events, particularly those in the molecular world which we call chemistry, occur in milliseconds or less, and it is therefore natural that the chemist should seek methods for the study of events in microtime.

My own work on "the study of extremely fast chemical reactions effected by disturbing the equilibrium by means of very short pulses of energy" was begun in Cambridge 20 years ago. In 1947 I attended a discussion of the Faraday Society on "The labile molecule." Although this meeting was entirely concerned with studies of short-lived chemical substances, the 400 pages of printed discussion contain little or no indication of the impending change in experimental approach which was to result from the introduction, during the next few years, of pulsed techniques and the direct spectroscopic observation of these substances. In his introduction to the meeting, H. W. Melville referred to the low concentrations of radicals which were normally encountered and said "The direct physical methods of measurement simply cannot reach these magnitudes, far less make accurate measurements in a limited period of time, for example 10^{-3} sec."

Work on the flash photolysis technique had just begun at this time and details of the method were published 2 years later (*1, 2*). Subsequent developments were very rapid, not only in Cambridge but in many other laboratories. By 1954 it was possible for the Faraday Society to hold a discussion on "The study of fast reactions" which was almost entirely devoted to the new techniques introduced during the previous few years. They included, as well as flash photolysis, other new pulse techniques such as the shock wave, the stopped-flow method, and the elegant pressure, electric-field-density, and temperature-pulse methods described by Manfred Eigen. Together with pulse radiolysis, a sister technique to flash photolysis which was developed around 1960, these methods have made possible the direct study of nearly all fast reac-

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