THE EARLY UNIVERSE

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RESUMEN. En el artículo se pasa revista a algunos problemas básicos actuales en cosmología tanto observacional como teórica, y con especial referencia a investigaciones recientes relacionadas con el universo primitivo y a posibles implicancias de desarrollos en la Física de partículas.

ABSTRACT. The paper is a review of some current basic problems in observational and theoretical cosmology with special reference to recent investigations concerning the early universe and the possible involvement of developments in particle physics.

If current hot big-bang cosmology is basically valid then necessarily everything in the universe must relate to *the early universe*. This paper is intended to recall how some of the relations arise. It is concerned with:

Gravitation theory, calling attention to the fact that modifications are almost certainly needed near the big-bang singularity in a cosmological model.

Particle physics because, as has been remarked, the hot big-bang is the *ultimate particle accelerator* and so it should provide tests of such physics that could be had in no other way.

Friedman-Lemaître cosmological models which employ postulates concerning the *cosmical constant* Λ, *homogeneity*, *flatness* that are now appreciated to go back to the very early behaviour of the models.

Nucleosynthesis, the study of which reveals the baryon content of the universe and neutrino properties that also relate back to the early universe.

Galaxy-formation which requires fluctuations -in the contents of the universe- that are now inferred to have had some primeval character.

Constants of physics which must somehow arise from the early universe. They provoke the question as to whether, in any physically significant sense, there exist *other* universes.

Cosmical numbers which seem to be required, in addition to the constants of physics, to determine the early universe.

Finally it has to be asked, What is learned from the study of the early universe about cosmology in general, about physics in general?

In a sense the paper is an attempt to report briefly upon the state of cosmology at the end of 1983. Before dealing with the foregoing matters of interpretation it is necessary shortly to review the empirical situation.

THE OBSERVED UNIVERSE

The cosmic epoch (present) of observation is denoted by t_0, and suffix zero on any other parameter denotes its value at t_0. Thus H_0 is the present value of the Hubble *constant*. If we write, as in common practice, H_0 = 50h kms/s Mpc^{-1}, then nearly all empirical estimates yield

$$1 \lesssim h \lesssim 2$$

but within these approximate bounds, the empirical value is still uncertain.

Much of the recent observational work and its analysis is directed to the discovery of the large-scale structure of the Universe:

a) Statistical studies, particularly the work of Peebles (1980) and others on 2-point correlation and elaborations of this, have derived measures of the clustering of galaxies.

b) Detailed particular observations apparently reveal *strings* and *pancakes* of galaxies or clusters of galaxies that seem to compose a roughly defined lattice in three dimensions which then defines enormous roughly spherical *voids* on the scale of a million cubic Megaparsecs each. Opinions differ, however, as to the extent to which such an apparent structure is in fact fortuitous.

c) The *Lyman alpha clouds* discovered in the past few years are evidently intergalactic. They are expected to serve as important indicators of cosmic evolution, but they seem not to involve an important fraction of the mass in the Universe.

d) Evidence for the presence of *dark matter* in galactic halos, clusters of galaxies, etc., is much studied but it is still quantitatively inconclusive.

e) Non-zero rest-mass of a neutrino is still uncertain.

f) The existence of *exotic particles* remains speculative.

g) Strict upper bounds have been determined for anisotropies in the microwave background radiation.

h) Other backgrounds -X-ray, gamma-ray, cosmic-ray are studied with interest, but almost certainly are not of comparable cosmological significance.

i) *Primordial* abundances of D,(^{3}He), ^{4}He have been redetermined within carefully estimated bounds.

j) The *Baryon: photon ratio* has been estimated empirically in various ways; the favoured value appears to be $\eta \sim 10^{-9}$.

GRAVITATION

It is important to ask to what extent cosmology has tested specifically Einstein's theory of gravitation. Some predictions of relativistic cosmology depend only upon the adoption of a Robertson-Walker type metric. Gravitation is involved only if the predictions concern energy and stress in the model, in which case relations of these to the expansion factor R(t) of the metric are needed. If the relations are those given by Einstein's theory, the Friedman-Lemaître cosmological models result. The simplest of these is the well-known Eisntein-de Sitter (ES) model. This is often employed as a norm; in particular for any other model (or for the actual Universe) the density parameter $\Omega(t)$ can be defined as the ratio of the density in that model (or the mean density of the Universe) at cosmic epoch t to the density at the same epoch in an ES universe having the same Hubble constant at that epoch.

Barrow & Ottewill (1983) show that Friedman-Lemaître type universes exist for gravitation theories derived from a Lagrangian much more general than Einstein's. This may be important because, for one thing, if we do not regard Einstein's form of general relativity as final, then we need not assign special status to the ES model i.e. to the model having the apparently unique property $\Omega = 1$ for all t. Working strictly within the boundaries of Einstein's theory, is a strong temptation to infer that the actual Universe must correspond to the model for which $\Omega = 1$ since were one to advocate, for the present cosmic epoch, any value different from 1, there would be no *a priori* reason to prefer it rather than any other such value.

It is well-known that endeavours to *quantize gravitation* have a long history of non-success. In more recent times the view has generally been adopted that such quantization is necessary and significant within only the very early universe, perhaps only before cosmic time equal to the Planck time $t \sim 10^{-43}$s. More recently still, Adler (1983) has suggested that Einstein's theory should be regarded as a *long-wavelength effective theory* arising from a *fundamental theory* (the difference being significant probably only for the very early universe) more like other quantum field theories. But even on the scale of the solar system we have come to think of space-time and gravitation as inextricably interrelated. So if gravitation is in any way quantized in the early universe, where it must be so much more significant because of the enormously greater densities, we must expect our usual notions of space-time to be wholly inadequate. There seems as yet to be no satisfactory way of dealing with this situation.

HISTORY OF HOT BIG-BANG COSMOLOGICAL MODEL

What may be called the standard hot big-bang model universe has the following history: the big-bang being a singularity at t = 0:

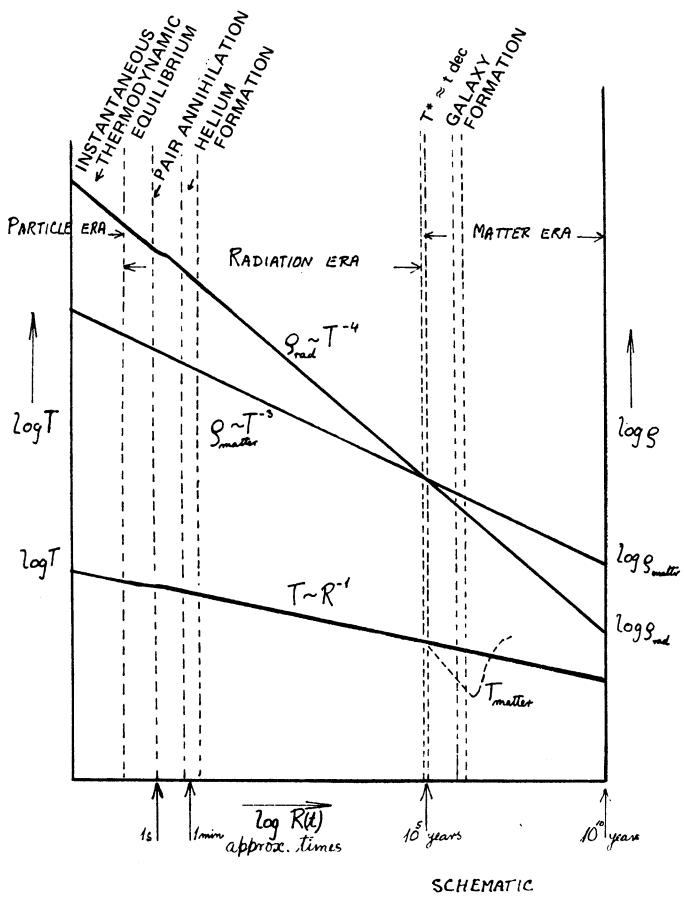

Fig. 1. Hot big-bang history.

Particle era (early universe) from say 10^{-43}s to 10^{-3}s (approx) during which there is at every cosmic epoch instantaneous thermodynamic equilibrium with regard to every possible physical process. Initial content of universe is inferred to be predominantly *quark gas* consisting of all forms of quarks and their anti-particles. As the expansion proceeds these then form hadrons and leptons and their anti-particles; this is followed by pair-annihilation leaving mainly atomic nuclei, electrons, neutrinos and photons. Thereafter the baryon-photon ratio η remains about constant at the estimated value $\eta \gtrsim 10^{-9}$.

Radiation era from about 10^{-2}s to about 10^{13}s (about 4 x 10^5 years) throughout which the energy in the photons is large compared with that in the matter (including rest mass). Let T(t) be the radiation temperature at cosmic epoch t. Up to t $\gtrsim$ 3 minutes in any neighbourhood there is instantaneous thermodynamic equilibrium in regard to all nuclear reactions. But around t $\gtrsim$ 3 minutes nuclear abundances are determined by reaction rates; as these rates fall off certain (primordial) abundances become frozen in, the only significant surviving nuclei being H, D, ^{3}He, ^{4}He. At t $\gtrsim$ t_{dec} $\gtrsim$ 4 x 10^5 years nuclei and electrons recombine so that the matter there becomes effectively transparent to the background radiations i.e. matter and radiation *decouple*.

Matter era t $\gtrsim$ 4 x 10^5 years, energy-density in the form of matter is dominant. The fact that decoupling occurs about the end of the radiation era t* is an arithmetical consequence of $\eta \gtrsim 10^{-9}$. There is no known *a priori* reason for the universe to be such that this coincidence should occur. After about the same epoch $T \propto (R(t))^{-1}$, where T is still the radiation temperature. After decoupling, so long as the matter remains evenly distributed, as the expansion of the universe proceeds, the matter remains evenly distributed, as the expansion of the universe proceeds, the matter temperature falls more steeply than the radiation temperature. On general grounds we should estimate that conditions were optimal for galaxy-formation at a redshift of about 100, certainly at a value of t small compared with the present age of the Universe at ourselves. After the formation of galaxies and stars therein, the release of stellar energy tends to heat up any remaining raw material (but it is clear that such material is almost certainly not is thermodynamic equilibrium, so that it does not possess an ordinary thermodynamic temperature). This and the falling density of such material strongly indicates that, once considerable galaxy-formation has occurred such formation will be unlikey to continue, i.e. the epoch of galaxy-formation may be expected to be rather well-defined.

It has to be emphasized that this is in the first place the history of a model universe only. Even as a model it has rather obvious shortcomings. Most of what happens in the *particle era* of the model is still conjectural. For the rest, the physics seems fairly secure, but the model seems to depend on rather arbitrary simplifying assumptions. Finally, from one standpoint the whole purpose of such a model is to account for the existence of galaxies. The model as it stands provides the raw material and an epoch propitious for constructing galaxies from it. But it does not yet furnish a satisfactory mechanism for this crucial development.

As described above the model has been known since about 1970. In recent years a great deal of work has been in progress on:

(a) The particle physics directly concerned in the particle era and that then provides the basis for the whole theoretical structure.

(b) The analysis of the *simplifying assumptions* mentioned above.

(c) The study of possible mechanisms of galaxy-formation and conditions needed in order that they may operate. As we shall see -and this may not be surprising- the basic resolution of (b), (c) seems to depend upon the resolution of (a).

Then there is the all-important question of the correspondence between the model and the actual universe of experience. Of course we can never be certain about this. But ever since the model was first proposed it has been widely accepted as at anyrate generally plausible. During this time many problems have arisen, some of which we are discussing here. But it seems fair to claim that no feature has emerged to render the model less plausible. In fact, whatever may happen to it in future, it seems to be the only basis we have at present upon which to discuss the large-scale nature of the Universe around us.

POSTULATES OF BIG-BANG COSMOLOGY: ISOTROPY AND HOMOGENEITY, COSMICAL CONSTANT

The discussion of the preceding section applies to a suitably selected Friedman-Lemaitre (FL) model. It is important to examine the postulates upon which such models depend. FL models were required to be homogeneous and isotropic originally on the grounds of mathematical simplicity. Then, as regards application to the actual Universe, these properties were supported by its empirical isotropy (within the limits of observation) and a postulated -but seemingly inevitable- *cosmological principle*. Only more recently has it been appreciated that awkward physical assumptions are involved. These have become known as:

1) *Horizon problem* Qualitatively in most models concerned there are regions that, according to the postulates, at any cosmic time t behave identically but were outside each others horizons at some earlier cosmic time $t' < t$. So the question is, How did they *know* how they should behave at t'? Quantitatively, according to an estimate by GUTH (1981), when the contents of a volume element of the early universe were established, these had to be the same in some 10^{83} causally disconnected such regions!

2) *Flatness problem* The parameter $\Omega(t)$ was defined above. If a FL model is compared with the observed Universe it is inferred that $0.03 \leq \Omega_0 \leq 1$. But even if we extend this range to $0.01 \leq \Omega_0 \leq 10$ which should cover all empirical uncertainties, GUTH shows that in the early Universe at the epoch when the temperature was, say, $T = 10^{17}$ Gev, it would have been required that $\Omega = 1$ to within 1 part in 10^{55}. That is, unless the early Universe had been of ES type to fantastic fine-tuning it would long ago have collapsed or blown itself up. In other words, the early universe that led to the Universe we know must have been an unimaginably unstable system.

These are no arguments against the Universe being as we find it to be! We have to take it as we find it, but then we have to face the problem as to how it got that way.

There is another feature of the Universe as we find it. When Einstein first applied general relativity to the *cosmological problem*, he included the *cosmical terms* in his equations. These are components of the fundamental tensor multiplied by a constant Λ. This *cosmical constant* is required by the theory to be an absolute constant, i.e. it must not depend on space-time coordinates. The Friedman-Lemaître equations may be written with the cosmical terms included and then solved for Λ. The result involves various parameters of the model. Using observed properties of the actual Universe, bounds can be placed upon these parameters. These yield $|\Lambda| < 10^{-120}$ in absolute units. This is derived for the present cosmic epoch, but by definition Λ cannot depend upon the epoch. Thence Hawking (1983) and Kibble (1983) infer that Λ is the quantity in physics most accurately measured to be zero. In fact the FL models under discussion are those for which $\Lambda = 0$ is postulated.

INFLATION

Several properties of *vacuum (quantum) states* yield in effect non-zero values of Λ. These effects are significant only at very high energies. There is a suggestion that in the early universe a phase-transition took place when an original unified (*electroweak*) force split into electromagnetic and nuclear-weak constituents, as, with falling temperature, the Glashow-Salam-Weinberg theory would require. Times of order 10^{-35}s after the big-bang have been mentioned. During the transition a vacuum effect of this sort is inferred to have produced an enormous *cosmic repulsion* that caused the universe to inflate by a factor estimated at about 10^{20}. When the transition was complete, and the two kinds of force had been *frozen out* with their familiar characters, the repulsion would vanish.

This huge expansion, it was claimed, would smooth away initial irregularities so as to produce the high degree of homogeneity and isotropy inferred for the early stages of the *normal expansion*. It would remove the objection that the homogeneity had seemed to hold good between regions that could not have been in causal connection where it was first established. Also reasons were adduced for concluding that the normal expansion would start from a state with $\Omega \approx 1$. Finally everything would be consistent with $\Lambda = 0$ for the normal expansion.

Thus is began to appear that the horizon and flatness problems and that of the vanishing of Λ had indeed been resolved.

There was one rather technical difficulty. As has been indicated, general relativity cannot admit a *cosmical constant* that is different at different times. But in principle the effect of the vacuum states is not *precisely* the same as that of a non-zero cosmical constant.

The original inflationary model has now come to be rejected on more fundamental grounds of the particle physics involved. Physicists seem now to favour a *bubbly* early universe. One version envisages the observable universe as arising from the inflation of one small *bubble* of the early state (Kibble 1983). Another regards even the present universe as *bubbly* on a micro-scale, but smooth on the scale on which we observe it (Hawking 1983). All that can be said at the moment seems to be that the solutions of the problems of this section almost certainly lie in the phenomena of the early universe.

NUCLEOSYNTHESIS AND THE BARYONIC CONTENT OF THE UNIVERSE

The sort of study of the large-scale structure of the Universe carried out by Peebles (1980) yields an estimate of the present mean mass-density ρ_0 in the Universe

$$\rho_0 = 4.7\times10^{-30} \quad \Omega_0\, h^2 \ \mathrm{gcm}^{-3},\ H_0 = 50h \ \mathrm{km/s\ Mpc}^{-1}$$

and the estimate is given by $0.03 \lesssim \Omega_0 \lesssim 1$.

The mean density of galactic matter is estimated to be $\rho_G \approx 1.4\times10^{-31}h^2$ gcm^{-3} (Weinberg 1972), which happens to agree with $\Omega_0 \approx 0.03$.

If primordial abundances of deuterium and helium are inferred from observation and if the measured temperature of the background radiation $T_0 = 2.7$ K is used, two estimates of the present baryon density are derived (e.g. Pagel 1982).

All the results are shown in Fig. 2. We see in particular: If $H_0 \approx 50$ km/s Mpc^{-1} all the matter could be baryonic with Ω_0 not much more than 0.03; all the galactic mass is presumably baryonic, and it is seen that it is probably not much less than the total mass.

If $H_0 \approx 100$ km/s Mpc^{-1} then either there is much non-baryonic matter or Ω_0 is much smaller than estimated (about 0.01); but then we encounter another more serious difficulty, since the amount of galactic matter would come out at about three times the baryonic matter.

Of course the uncertainties in the estimates may be more than is supposed. But as things stand, a value of H_0 not much different from 50 km/s Mpc^{-1} gives the most acceptable results.

The problem of dark matter has been mentioned, but we do not pursue it. At present there seems to be no positive evidence for a significant amount of non-baryonic mass. As we said earlier, there might appear to be *a priori* reasons for expecting $\Omega \approx 1$ in which case the present section would indeed indicate that the greater part of the mass would then have to be non-baryonic. But we have mentioned reasons for $\Omega = 1$ possibly not being the magical value having unique merit. But even if Ω was close to unity in the past it could have reached any other value at the present cosmic epoch without such a value having any particular significance other than being the value at the epoch when we happen to concern ourselves about it.

Finally we remark that it would seem odd that, if a significant amount of non-baryonic matter exists, this should be just the right amount to produce $\Omega \approx 1$.

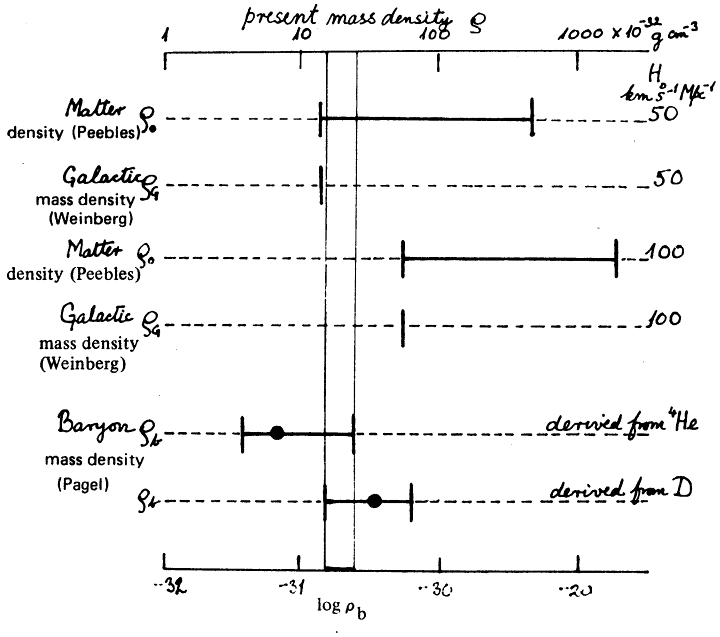

Fig. 2. Empirical mass density estimates.
Baryon-density derived by Pagel from his preferred abundances with bounds: vertical lines show range of ρ_b within both sets of bounds.

GALAXY-FORMATION

As remarked earlier the formation of galaxies may be regarded as the culminating problem of cosmology. In a universe in which there are no irregularities of density there is *ipso facto* nothing that can cause irregularities. Therefore if there exist irregularities -in the form of galaxies, say- there can never have been a state with no irregularities. So our problem is not to ask how irregularities, or condensations, were first formed, but to begin by asking what irregularities at an earlier stage could have led to galaxies at the present stage. Then we have to ask about the nature of the earliest irregularities in the sequence that we are able to contemplate. Thus the first stage is, in a cosmological model of the sort under discussion at some epoch between helium-production and *decoupling*, to suppose some arbitrary density fluctuations δ_ρ/ρ to be present, and then to study the developments as the contents of the model expand through decoupling. Fluctuations of two general characters are considered, the names not having a strictly literal significance:

1. *Adiabatic* fluctuations: these involve both the matter and the radiation present at the outset. So long as the matter is ionized i.e. up to the time of decoupling, radiation damping is strong for condensations of relatively small mass. It is inferred that condensations surviving recombination have masses mostly in the range 10^{12} to 10^{14} solar masses. Such a condensation is expected to collapse as a *pancake*. This then is inferred to fragment into clusters of galaxies. Peebles (1980) recognizes three characteristics lengths associated with the whole process.

2. *Isothermal* fluctuations: these involve the matter alone. Radiation in this case causes less damping. No characteristic lengths emerge which some cosmologists think may be more in agreement with observation than is case 1. First condensations in this case may be on the scale of globular clusters. These would then be expected to merge to produce galaxies which in turn would be expected to form clusters.

The most recent review is that by Shandarin *et al.* (1983). What appears to be a useful body of theory has been constructed, but it can scarcely be claimed that *galaxies* have yet been constructed. Some phenomenon besides gravitational instability seems to be needed; probably shocks between forming condensations or within a collapsing condensation (McCrea 1982, 1983).

3. *Primeval* fluctuations: The theory does at anyrate confirm the reasonableness of postulating *some* fluctuations in the universe prior to decoupling. Shortly before decoupling in the actual Universe these could not have exceeded $\delta_\rho/\rho \stackrel{\sim}{\lambda} 10^{-4}$, since it has been shown that larger fluctuations in the contents of the Universe at the epoch concerned, which is about the epoch of last interaction between much of the radiation and matter, would cause fluctuations in the present microwave background radiation in excess of any observed. Also it is inferred that fluctuations weaker than this would not be of interest for galaxy formation. So the existence of fluctuations $\delta_\rho/\rho \stackrel{\sim}{\lambda} 10^{-4}$ at this epoch is taken to be confirmed.

From what was said at the beginning of the section, these must be consequences of something more primitive. Here we have to ask what our problem really is. Are we -as is traditional in the subject- to contemplate a primitive universe that is as uniform as may be and to try to account for fluctuations from perfect uniformity? Or are we to contemplate a primitive universe that is as chaotic as may be, and to try to account for a large-scale uniformity subsequently attained?

The earliest state of the universe that existing physics can envisage is one in which everything is quantized. It is an intrinsic feature of a quantized system to exhibit *quantum fluctuations*. If then the most primitive state of the universe that we are able to consider must show such fluctuations, it is natural to ask if these could leave an imprint that will survive through all subsequent phases and finally produce the fluctuations that lead to galaxy-formation. It has in fact been suggested that inflation would obliterate all other primitive fluctuations, if any, and leave *only* the imprints of quantum fluctuations. But one is not aware of any firm inferences.

From time to time cosmologists have sought to construct a cosmological model that starts from a state of primeval chaos and that somehow -maybe through inflation- attains a high degree of large-scale uniformity. The fluctuations producing galaxies would then be relics of the early chaos. In principle, this appears to be a natural way to think of a universe that could never have been without irregularities in its contents. But the objection would be, were we to wish to retain the broad features of the hot big-bang leading to the epoch of decoupling, then homogeneity to within the degree $\delta_\rho/\rho \lesssim 10^{-4}$ would have to be achieved at a stage before decoupling. No one has explained how this could come about.

There have been intermediate suggestions. Instead of primeval chaos, the notion of *primeval turbulence* has been advanced, but without much profit.

Another approach that has been talked about in recent months is to ask whether it is possible to learn anything about primeval fluctuations from the present observed large-scale structure of the Universe. Some writers have tried to regard the cellular or network structure of strings of galaxies and clusters of galaxies as a *fossil* of structure in the early universe. This is tempting, but what evidence there is from numerical simulations seems to be against the notion. Such simulations seem to show, on the one hand, that any large-scale structure shown by galaxies and clusters when first formed would be unlikely to persist. At the same time they have been claimed to show that, at anyrate in a neutrino-dominated universe, *clustering [of galaxies] into filaments and pancakes* can result as time goes on from gravitational interaction (Centrella & Mellot 1982, see also review by Helfand 1983).

We have to conclude this section with the rather unsatisfying conviction that the fact of the astronomical universe being composed of galaxies must be determined by some property of the early universe, but no one knows what it is.

PHYSICS

It is the existence of the constants of *physics* that makes physics what it is. Basically, they arise because everything in physics is *quantized*. They lead to natural units, often called Planck units. If our concepts are valid, this would enable us in principle to exchange precise physical information with physicists anywhere in the Universe. Also it is to be noted that a constant of physics has an operational existence that transcends any particular *model*.

The constants enter crucially into the *horizon problem*. For in the cosmology of the very early universe we implicity assume that we may take all the constants to be the same in any two regions, whether or not they have every been in causal contact with each other.

All properties of the world of astrophysics depend upon the values of a few fundamental constants. For example, bounds for the mass of an asteroid, a planet, a star can be set in terms of such constants (Press and Lightman 1983). This general circumstance leads to what has become known as *the weak anthropic principle*. For it implies that in an evolving universe man can exist within only a restricted region of space-time determined by the values of the constants. This determines the nature of man's direct experience of the Universe; this is the principle.

A *strong anthropic principle* can be expressed in several ways which all amount to the postulate that the constants of physics have to be such as to admit the existence of beings like us.

The weak principle simply accepts that the constants of physics have certain values and then simply notes that these permit us to exist when the universe is in a certain state. The strong principle looks at the situation the other way round. It notes that we do exist and attempts to say that therefore the constants of physics must have such and such values.

Such ideas lead to certain fundamental questions, including:

a) Do there in any sense *exist* other universes in which the constants have values different from those in *our* universe?

b) Are there constants of cosmical physics that are not related to those of microphysics?

COSMICAL NUMBERS

All known constants of physics concern entities that exist, but not the quantities that exist so as to make the Universe what it is. As we look at physics now, there must be some numbers that specify the actual Universe.

The number of dimensions of spacetime, seems to be a *given* constant of the Universe. A universe would be very different were the number other than 4 (i.e. space 3 + time 1) (Barrow 1983). Some recent unified theories employ space-times with dimensions up to 11. But the status of the dimensionality is the same.

Rees (1983) has indicated another *three basic numbers that characterize our Universe*:

The Robertson-Walker curvature radius $R(t) \approx 10^{60}$ Planck lengths at our cosmic epoch.

The baryon:photon ratio $\eta \approx 10^{-9}$, effectively independent of t.

The amplitude of fluctuations that triggered galaxy-formation $\delta_\rho/\rho \approx 10^{-4}$.

At present we do not know why these have or had these values, or whether we should expect ultimately to relate any of them to the constants of physics.

COSMOLOGY AND PARTICLE PHYSICS

A remarkable development in very recent years -referred to several times in this paper- is the apparent coming together of cosmology and the latest work in *particle* and *high energy* physics, in the discussion of the very early universe. This may seem inevitable because of the early universe providing the *ultimate particle accelerator*, if anything like the current picture is valid. Thus, in studying the early universe, we may expect to encounter phenomena of which we could become aware in no other way.

On the other hand, it may seem odd that there should exist any such phenomena, i.e. that ordinary matter should possess properties that are called upon to play any role during no more than, say, 10^{-40} or 10^{-30} second in its whole existence. However, to take an example that has nothing to do with the early universe or anything else in cosmology, quantum physicists are able to predict and verify happenings to do with liquid helium that Nature herself and *never* before witnessed. Such considerations make the behaviour of even *simple* matter appear mysterious.

In conclusion, it is natural to ask two questions:

1. What has been learned from cosmology about particle physics? Cosmology has shown that with high probability the number of sorts of neutrino is 3 (or 6 counting anti-particles as well). It sets bounds to the rest-masses of these particles. As a matter of history it led to the discovery in the laboratory of the crucially important excited state of the ^{12}C nucleus.

2. What has been learned from particle physics about the Universe?

Particle physics has offered detailed pictures of the very early universe, but so far these have not predicted new observable phenomena nor explained old ones -although it may be claimed that the notion of inflation has come near to accounting for the large-scale homogeneity of the present universe.

This seems to be a meagre yield of definite results. But the present situation is causing physicists to think more deeply than perhaps ever before about the fundamentals of physics and cosmology. A much greater harvest may be expected in the near future.

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DISCUSSION

Branham: What is the status of the cold big-bang cosmology?

McCrea: G. Lemaître first contemplated a "big bang" some 50 years ago; it was not specifically "hot". Whatever else a big bang may signify, it certainly denotes a tremendous energy density needed for the ensuing expansion. It is difficult to contemplate matter so organized that it carries this energy without being in a state that we should describe as hot. Nevertheless a few workers do from time to time still seek to investigate the possibility of a very early state that can reasonably be described as cold. I do not think that they have established any convincing advantage in the concept.

Mirabel: Why are shocks necessary for the formation of Galaxies?

McCrea: Shocks are a good way of bringing material to a state of gravitational instability. I think it is now widely accepted that the formation of stars within the Galaxy is triggered by shocks produced by interstellar clouds colliding in spiral arms or by supernova outbursts occuring in or near a cloud. In particular, it has been suggested that a supernova outbursts triggered the formation of the Sun and its planets. Here I am simply contemplating similar processes on a greater scale.

Wielebinski: How do you take into account the evolutionary sequence of galaxies? Do you expect a protogalaxy-forming now? Some extragalactic HII region, seem to be galaxies in their formation.

McCrea: As regards galaxies I was speaking in general terms only of their origin and not of their subsequent evolution. I should point out, however, that whereas successive generations of *stars* within a galaxy may be formed every time by about the same processes, owing to the expansion of the Universe the possibility of forming new *galaxies* decreases quite rapidly as time goes on. Nevertheless, the process I have outlined for forming galaxies may be not *highly* efficient, so that a significant amount of raw material may remain after the first galaxies have been formed. Some of this material might indeed form galaxies somewhat later. Also if two galaxies each containing a considerable amount of interstellar material collide, then the result would be generally similar to those of the collisions that -I suggest- produced the first galaxies. A new galaxy might be formed or new globular clusters might be added to one or both the colliding galaxies.

Peimbert: What can be said about the big bang singularity? Is there any work going on about it? What happenned before it?

McCrea: The first thing that can be said about the big bang singularity is that it *is* indeed a singularity in the mathematical description. This renders it meaningless, within the description, to speak to anything happening *at* the big bang. It is certainly meaningless -again within the standard mathematical description- to speak of anything *before* the big bang. The mathematical model contains no events that can meaningful be said to be before the big bang.

So far as this goes, I think it is satisfactory and self-consistent that the situation is like this. Perhaps it is best thought of in terms of the logarithm of the cosmic time i.e. $\tau = \ln t$, instead of t itself. There is no value of τ for a limit $t = 0$.

This is far from being a complete answer to the question. I suppose one might claim that the main aim of cosmology is to try to find an answer!

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