Summary: This article starts with a summary of the history of the Universe, as given by big-bang cosmology about a decade ago. It attempts then to review some of the main developments that have taken place since that.

Refined studies of the relative abundances of the light elements hydrogen, helium and deuterium have yielded improved limits upon the value of the baryon: photon ratio \( \eta \). There have been extended assessments of the amounts of dark matter associated with galaxies and systems of galaxies. In combination with the estimates of \( \eta \), these have facilitated discussion of the amount of nonbaryonic mass that may exist in the Universe. This is naturally related to work upon the possible rest-mass of the neutrino, but precise inferences are not yet forthcoming.

Recent work on the large-scale structure of the Universe is mentioned and this leads to a discussion of the origin of condensations in big-bang cosmology. A sketch of a model for galaxy formation indicates that big-bang cosmology seems capable of accounting for this, provided a theory of the origin, in this cosmology, of inhomogeneities of any sort is forthcoming.

Introduction

Cosmology has come to have two main purposes: to predict the astronomical universe as observed, and to retrodict the early history of the universe as far back as possible. Any such comprehensive statements are oversimplifications; for instance we have to have some sort of a model even to describe the

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Cosmology-galaxies-baryonic matter-nuclear abundances
“observed” universe; or again, the second purpose tends to beg the question of it being meaningful to discuss some sort of “beginning” of the whole physical universe. With such qualifications to the statements, is seems that the second purpose is attracting more interest at the present time, but that it is a matter of the most fundamental physics rather than of astronomy and astrophysics. In this paper I am concerned mainly with the first purpose, which may be said to be the central purpose of physical astronomy at this time.

In 1917 modern cosmology began rather accidentally with a famous paper by A. Einstein (1917). That aspect was accidental because Einstein’s main concern was to satisfy himself that his new theory of general relativity (GR) was free of internal contradiction by discovering at least one complete system that it could treat self-consistently. His other concern was to try to determine the extent to which GR could be said to accommodate the so-called “Mach principle”.

Einstein never showed himself to be much interested in the actual astronomical Universe. I mention this - not because I have any wish to embark upon a history of modern cosmology - simply in order to recall that much of that history has involved such fortuitous elements. Its advance - if that word is justified - has been far from an orderly progression of observational and theoretical discoveries.

The very existence of any such discipline is astonishing. The possibility of what everyone now calls the big-bang was first disclosed in independent papers by Friedman (1922) and Lemaître (1927). These were almost completely ignored until after the empirical discovery by Hubble (1929) of the “expanding universe”.

While some people then became impressed by the circumstance that GR had thus in a general way predicted this startling behaviour, no-one at the time can have supposed that the Friedmann-Lemaître type of model might offer more than the crudest indication of an account of the actual cosmos in all its bewildering complexity.

Yet now, more than half-a-century later natural philosophers solemnly discuss what could have happened in about the first $10^{-43}$ second of precisely such a model.

In order to lead into a brief survey of where the subject stands to-day (1983), one has to begin somewhere - certainly some time later than the first $10^{-43}$ s. It is in fact convenient to begin about a decade ago because by then the general history of a fairly standard hot big-bang cosmological model had been worked out.
This was, and still is, believed to be physically sound so far as it goes, but it had not yet been seriously applied to the two purposes mentioned at the outset.

The General History of the Hot Big-Bang Universe

We consider a Friedman-Lemaître model with the parameters:

\[ t = \text{cosmic time} \]

\[ R(t) = \text{expansion factor} \quad H = \text{Hubble factor} \quad \dot{R}/R \]

\[ \kappa = \text{curvature constant} \quad (1, 0 \text{ or } -1) \]

\[ u = \text{radiation density} \]

\[ \rho = \text{matter density} \]

\[ T_\gamma = \text{radiation (black-body) temperature} \]

\[ \eta = \text{baryon/photon ratio} \text{ (can be treated as independent of } t \text{)} \]

\[ X, Y, X_D = \text{primordial abundances by mass of hydrogen, helium, deuterium (i.e. before star-formation)} \quad X + Y \approx 1. \]

Values at the present epoch \( t_0 \) are written \( H_0, T_0, \) etc. The cosmical constant \( \Lambda \) is taken to be zero. A particular model of the class is characterized by the values of \( H_0, \rho_0, T_0, \eta \).

In the earliest time that concerns us here the density and temperature are so great that, in spite of the high rate of expansion of the universe, all particle-interactions proceed so fast that there is thermodynamic equilibrium at every instant, characterized completely by the instantaneous values of density and temperature. Then there is an epoch about \( t = 1 \) second, when particles and antiparticles mostly annihilate each other leaving only whatever imbalance there may be of one sort or another. At this stage \( u \gg \rho \), so that the universe is in a radiation-dominated era.

Within a time of the order of a minute after that, nuclear reactions proceed at non-equilibrium rates until they die out altogether never to be resumed until they proceed again as thermonuclear reactions in stellar interiors. During this interval a certain nuclear composition is "frozen into" the baryonic matter. So far as ordinary astronomy goes this is "primordial" matter. It consists of about 70 to 80\% by mass of hydrogen and the rest
Fig. 1 History of hot big-bang cosmological model (schematic).
helium, apart from a fraction almost certainly less than 0.1% of deuterium, and no significant amount of any other element. The precise primordial values of \( X, Y, X_D \) for a model depend upon the value of the parameter \( \eta \).

As the expansion of the model universe proceeds, elementary theory shows that to a completely adequate approximation

\[
T_\gamma \sim R^{-1}, \ u \sim R^{-4}, \ \rho \sim R^{-3}.
\]

Thus sooner or later there must come a temperature \( T_\gamma = T^* \), say, at which \( u = \rho \); at any significantly later time, so long as expansion continues, \( \rho \gg u \), and the universe is in a matter-dominated era.

In view of what emerges below, it may not be assumed that the density \( \rho \) is due entirely to baryonic matter. However, except in the very early universe, any non-baryonic matter would be transparent to the radiation responsible for the density \( u \). The primordial matter as described, so long as \( T_\gamma \) is large enough for the hydrogen to be considerably ionized, is opaque to the radiation. However, as \( T_\gamma \) decreases in consequence of further expansion, it will reach a value \( T_\gamma = T_d \), say, when the ions recombine and the material becomes transparent to the radiation. The matter and the radiation are then said to be “decoupled” (hence the notation \( T_d \)). The usual estimate for this purpose is \( T_d \approx 3000 \text{ K} \).

After decoupling the temperature of the matter \( T_m \) falls off more steeply than \( T_\gamma \); at any rate until there is a release of energy after some formation of condensations. Meantime the fall of \( T_m \) is of course generally favorable to the occurrence of condensations.

There is no evident connexion between the temperatures \( T^* \) and \( T_d \).

Nevertheless, it so happens that in models of interest these are found to have about the same value. No one has yet discovered any deep reason for this, and so we accept \( T^* \approx T_d \approx 3000 \text{ K} \) as a coincidence that happens to simplify the presentation.

The other empirical numerical values that have to be mentioned are \( T_0 \approx 2.7 \text{ K} \), which seems to be well-confirmed, and \( H_0 = 100b \text{ km s}^{-1} \text{ Mpc}^{-1} \) where most observations yield a value of \( b \) in the interval \( \frac{1}{3} < b < 1 \).

We recall that for all the models in the class considered \( t_0 < H_0^{-1} \approx 10^{10} b^{-1} \) years.

The evaluation of \( \rho_0 \) will be considered below.

At this stage the circumstance to be noted is that models in this class have qualitative properties-isotropy, homogeneity, presence of background
radiation - that match those of the actual Universe, and that a range of the models admit values of $t_0, \rho_0, T_0, Y$ that are in generally plausible quantitative accord with those of the "smoothed-out" actual Universe. Also such models predict no features that critically conflict with observation of the Universe.

This may appear to be a meagre outcome of the huge labour of observation and theory that has gone into the subject in more than 50 years. On the other hand the fact that all that effort has not brought to light any nonsense in this model-making is surely an impressive reassurance that this model-making is truly meaningful. Cosmologists are encouraged to proceed further beyond this stage and this they have tried to do in the past 10 years or so.

**Significance of helium and deuterium abundances**

The calculated values of $Y, X_D$ mentioned in the preceding section are obtained using a great amount of information about nuclear reaction rates. But the results have long been known to have certain simple properties.

\(a\) The larger the value of $\eta$ - that is the greater the greater the baryon density relative to the photon density (in absolute value $\eta$ is a very small ratio) - the larger the calculated value of $Y$ - in effect the abundance of helium relative to hydrogen.

\(b\) These is, however, a range of $\eta$ in which it increases about a hundred-fold while $Y$ increases only about from 0.25 to 0.30.

\(c\) The larger the value of $\eta$ the smaller the calculated value of $X_D$ - the relative abundance of deuterium.

The properties \((a), (c)\) indicate a most important possibility. Empirical values of $Y, X_D$ ought to provide bounds for the fundamental parameter $\eta$. Why was this possibility not seriously exploited until very recently?

Roughly speaking it was because the primordial abundance of helium seemed to lie in the range given in \((b)\) in which the theoretical value of $Y$ is extremely insensitive to $\eta$, and because the abundance of deuterium is very difficult to determine. Here it has to be appreciated that
deuterium is cosmically an abundant element; by number of atoms it is comparable to iron; on the other hand, it is a rare isotope of hydrogen, which is mainly what leads to the difficulties of measurement.

Helium is the chief product of nuclear reactions in stars, and, so far as is known, no reactions consume much of the helium in the universe. Therefore if the abundance of helium is measured anywhere in the universe the result should be an upper bound to its primordial value $Y$. The present renewed interest in the measurements is because some values are being found that are significantly lower than any previously found. Moreover, these latest values fall on a part of the $Y, \eta$ curve where $Y$ is more sensitive to $\eta$. Thus they lead to a significant upper bound for $\eta$. The deuterium nucleus is fragile as such things go, and many nuclear reactions in stars destroy deuterium.

So far as is known, none of these reactions generates any significant amount of deuterium. Consequently all the deuterium now in the Universe is primordial. Any significant measurement of its abundance - one not confused by "chemical" effects - yields a lower bound to the primordial value $X_D$. Because $X_D$ increases with decreasing $\eta$, this unfortunately again leads to an upper bound for $\eta$ - a lower bound would obviously have been more useful, but it is at any rate instructive to see to what extent the two evaluations are mutually consistent.

Applications. Last year Pagel (1982) reviewed all the then available evidence. Thence he inferred his "preferred value" of the abundance $Y \approx 0.23$ with lower and upper limits 0.21, 0.25; his "preferred value" of $X_D \approx 5 \times 10^{-5}$ with limits $2 \times 10^{-5}$, $2 \times 10^{-4}$. Using $T_0 = 2.7K$ to translate $\eta$ into the present baryonic mean density and standard $Y$, $\eta$ and $X_D$, $\eta$ curves, Pagel then obtained the corresponding estimates of this density; these are shown in Figure 2. It is seen that the intervals of the estimates overlap in only the interval $1.8 \times 10^{-31} \lesssim \rho \text{ baryon} \lesssim 2.5 \times 10^{-31} \text{ g cm}^{-3}$.

This year Gautier and Owen (1983) have published highly intriguing new estimates. They recall the widely accepted inference that the planet Jupiter is an unmodified specimen of the material from which the Solar-System was formed about $4.6 \times 10^9$ y ago, and further that the atmosphere of Jupiter retains the original relative abundances of hydrogen, deuterium and helium - that is, it is believed that significant differentiation of these gases has not yet occurred. The authors derive these abundances from observations made during
Fig. 2. Present mean density of all matter, baryonic matter, luminous matter.
the Voyager encounters with Jupiter and they discuss their results critically in
the light of such previous surveys as that of Pagel (1982). The outcome, so far
as helium is concerned, seems to be a confirmation of Pagel’s estimate
\( Y \approx 0.23 \) but with a sharpening of the bounds to \( 0.22 \lesssim Y \lesssim 0.24 \).

As regards deuterium the authors use this range of \( Y \) to infer from
the \( Y, \eta \) - curve the corresponding range of \( \eta \). From this the \( X_D, \eta \) - curve then yields a range for primordial deuterium \( 10^{-4} < X_D < 11.6 \times 10^{-4} \). These values are notably larger than Pagel’s, which are independent
of the estimates of \( Y \). Gautier and Owen obtain from the Voyager observa­
tions of Jupiter the deuterium abundance \( (5.5^{+15}_{-14}) \times 10^{-5} \). Thence
they conclude that between the origin of the Universe and that of the Solar
System there was much greater depletion of deuterium than has hitherto been
supposed - or else the standard big bang model is not acceptable. Taking this
view, the authors do not use the Jupiter value of the deuterium abundance in
order to estimate \( \eta \).

It may be added that Gautier and Owen, along with some others, accept
that some differentiations has taken place in the atmosphere of Saturn, so
that unfortunately the Voyager observations of that planet are not helpful in
the present context. However, the notion that a space mission to a member
of the Solar System, in this case, Jupiter, should enable astronomers to esti­
mate the number of baryons in the cosmos is intriguing - to say the least.

Returning to this matter of the mean baryon density the sharpened
limits on \( Y \) are found to place this in the range \( 5 \times 10^{-32} \lesssim \rho \text{ baryon} \lesssim 1.3 \times 10^{-31} \) without any reference to deuterium. This is not greatly different
from the range permitted by Pagel’s results for helium and deuterium. Verg
recently, values in even closer agreement with Pagel’s have been published
by Barrow and Morgan (1983).

**Present mean density - numbers of systems.**

The discussion in the last section brings us to the consideration of the
present density of the Universe. We are still seeking to compare it with a
standard big-bang model. In such a model the density \( \rho \) is a function
of cosmic time \( t \) alone. In the actual Universe the density varies enor­
mously from place to place. Nevertheless astronomers think it to be legitimate
to treat it as homogeneous in the large. A little more precisely, this means that
it must be possible to take a volume centred on any co-moving observer at his
cosmic time \( t \), of radius small compared to \( ct \), such that the mean density in this volume depends upon \( t \) only and not upon the particular observer.

We call this the mean density of the Universe at cosmic time \( t \), and we assume that we may use this as the empirical value of \( \rho (t) \) in the comparison model.

In discussing the "large-scale structure of the Universe" it has long been natural to think in terms of galaxies as the smallest units or components; this continues to be the case. We know that galaxies occur singly, in binary and multiple system, in groups, in clusters up to at any rate the order of a thousand members. Many astronomers further recognize superclusters. Some consider that galaxies and/or groups of galaxies are arranged in "strings" or "filaments" forming a sort of net-like framework in space, with enormous voids separating the filaments. One such void was "discovered" a couple of years ago, then its existence was doubted, but now astronomers seem on the whole ready to accept its reality. The observations as then interpreted imply the existence of a region of several hundred million light years in diameter seemingly devoid of bright galaxies.

It can readily be seen that the evaluation of a mean density under such circumstances is an exceedingly difficult and uncertain exercise. This is bound to be so for the simple physical reason that no astronomical phenomenon that we observe directly depends upon this mean. We require its value in order to infer what happened when, as we suppose, the Universe was in a much smoother state so that the mean density was the actual density, and it was in fact one of the few parameters that described the Universe.

There have been developed in recent years immensely powerful new techniques for carrying out surveys of the sky and for the quantitative analysis and classification of the results. Along with all this, there have also been developed powerful new techniques of mathematical statistics for the discovery and quantitative description of significant statistical features - e.g. the calculus of \( n \)-point correlation functions. The work of P.J.E. Peebles and the Princeton School deserves special mention (Peebles 1980). But there are two general difficulties in the way of such work. One is that, so far as I am aware, the more sophisticated parts were worked out before it was considered that any large scale directional effects might be significant. Anything in the nature of a filament of galaxies is characterized by a strong local directional feature.

I know of no objective technique for detecting this and assigning some measure of statistical significance to it. The other difficulty is that any extension of surveys to greater distance necessarily implies extension into the past.
(the "look-back" time) and so their interpretation is subject to unknown evolutionary effects. All this part of the work yields simply numbers of galaxies, or of systems of galaxies, classified in regard to apparent luminosity, and maybe class of galaxy, and, where possible, redshift.

*Masses of galaxies and clusters*

We have now to consider masses of galaxies and system of galaxies, basically in the present context in order to convert the numbers obtained by the work described in the preceding section into mass and mass-density.

**Luminosity mass.** The astronomer may list everything he can "see" - i.e. everything from which he can detect any sort of radiation - in a galaxy like our own or the Andromeda galaxy. From what he knows of the nature of the objects seen he can estimate their masses. Thence he derives what he may call a "luminosity mass" for the system concerned. Until a few years ago, this was generally assumed to be effectively the whole mass. It is still an important quantity, provided the astronomer has correctly interpreted his observations and provided his estimates of individual masses are generally reliable. For by definition it is the mass of everything the astronomer sees. If he has derived such a mass for a range of galaxies, then if he sees another galaxy that looks like one of these, he can assign to it a similar mass.

**Dynamical mass.** In the case of a galaxy with a well-defined disk it is often possible by observing the 21-cm radiation of interstellar hydrogen at various distances from the centre to obtain a so-called "rotation curve" for the system.

Thence, from the internal dynamics, the mass within these distances can be inferred. The greatest mass derived in this way is a lower bound for the total "dynamical mass" of the particular galaxy.

This is found in general to give a mass significantly greater than the luminosity mass and, in a number of cases, greater by an order of magnitude. Moreover, in a number of cases out to the distance to which the hydrogen line can be detected, the mass appears not to be converging, so that its actual value may be much larger than the lower bound. As is well known all
this is taken to be evidence for the existence of "dark halos", around the galaxies concerned, often greatly exceeding in mass the observed luminous components.

Again the internal dynamics of groups and clusters of galaxies leads to a determination of the total mass of the system concerned, which is usually referred to as the "virial mass". In general, this is certainly larger than the sum of the estimated luminosity masses of the observed component galaxies. In some it tends to confirm estimates of the dynamical masses of these galaxies.

However, there appear to be cases where the virial mass exceeds even the sum of any plausible values of the dynamical masses of the visible component galaxies. This is taken as evidence that a cluster as a whole may include a significant amount of dark matter which does not form part of any observed galaxies.

All that is said here is deplorably vague. Almost every case is subject to considerable uncertainties of observation or of interpretation. Also there are a few cases where dynamical masses have been derived by more than one method and where the results are discordant.

Further it seems that more refined dynamical theory is needed to obtain any trustworthy results in some instances. Nevertheless the cumulative evidence for the widespread existence in the Universe of some significant amount of "dark matter" now appears to be convincing.

**Present mean density of the Universe**

To date the most comprehensive work on the large-scale structure of the Universe is the book, having that as its title, by Peebles (1980). Having investigated most of the topics touched upon in the two foregoing sections of this paper, as regards the present mean density of the Universe he is still able to assert no more than that it "is thought to be in the range"

$$5.6 \times 10^{-31} \ b^2 \leq \rho_0 \leq 188 \times 10^{-31} \ b^2 \ \text{gcm}^{-3} \ \text{with as before} \ 0.5 \leq b \leq 1$$

In view of all the uncertainties that have been mentioned, this range may seem unexpectedly narrow! For comparison it is noted that Allen (1973) quoted as the mean density of "galactic material", in effect what is described above as "luminosity mass", the value $$2 \times 10^{-31} \ \text{gcm}^{-3}$$.

These values are shown in Figure 2 and the results we have discussed for
the present mean density of baryonic matter are also plotted.

If for the moment we accept the latter, we appear to be able to draw the conclusions: As expected, the results are consistent with luminous matter being all baryonic. If \( H_0 \approx 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and if the density of matter is not much more than that given by the luminosity mass, then all the matter in the Universe could be baryonic.

If \( H_0 \approx 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and if the density of matter is known to be much more than that given by the luminosity mass, then most of the matter in the Universe could not be baryonic.

If \( H_0 \approx 100 \text{ Km s}^{-1} \text{ Mpc}^{-1} \), most matter in the Universe is not baryonic, and we are compelled to admit the existence of much dark matter.

On the other hand, were we to know that almost all the matter in the Universe is in fact baryonic we should conclude that \( H_0 \leq 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and that there is not much dark matter.

This last would be probably the most satisfying as leaving as little as possible in the way of loose ends. However, what might be called the easiest conclusion would be that the density is somewhere about the middle of the permitted range, that this in itself places no restriction upon the value of \( H_0 \), that there is a plausible amount of dark matter which is necessarily non-baryonic.

All this shows how the recent studies of the abundances of the light elements turns out to have far-reaching implications.

Before leaving this part of the discussion one other consideration has to be dealt with. If dark matter preponderates over luminous matter, and if it were all baryonic, then this dark matter would compose the bulk of all baryonic matter. It could then be argued that the helium and deuterium abundances in the dark matter are those in which we ought to be interested, while the abundances in the luminous matter might be anything at all without making much difference to the overall picture. This would be true in a general way; however, as regards the most crucial question of the \( \text{He} : \text{H} \) ratio it is difficult though not impossible to see how the value in the luminous material could fall below the primordial value. If it cannot, then we are back to where we were, with any observed value serving as an upper bound to the primordial value \( Y \). Nevertheless the segregation of hydrogen and helium is possible and as already mentioned, Gautier and Owen (1983) find evidence that it has occurred in the atmosphere of Saturn. If it could have occurred in the process of forming a galaxy in such a way that more of the helium went into dark matter than into luminous bodies, then the overall density of baryonic matter
could be more than is at currently inferred. It would be important to look for any evidence of this. If helium does behave in this way, it would be expected that the helium abundance in luminous bodies could vary from one galaxy to another depending upon how much dark matter is associated with each galaxy. Kinman and Davidson (1982) have discussed recent measurements of the helium abundance in dwarf galaxies. They do in fact find a good deal of scatter; while they "suspect" that observational error is largely responsible, they say also, "it is possible, however, that some of the scatter has other origins".

One is not, of course, suggesting here that unless the mean baryonic density is greater than the estimates mentioned then the dark matter cannot be baryonic. So far as our discussion has gone, and provided $H_0$ is small enough, all the dark matter could be baryonic, only this would imply that the density of luminous matter has to be somewhat less than had been thought.

Reference should, however, be made also to an important contribution by Schramm (1982). He gives positive reasons for inferring that dark matter associated with single galaxies and small groups "has an appreciable if not complete baryonic component". He goes on to say, "The only place that may require there to be non-baryonic dark matter are the large clusters of galaxies". I think his discussion would imply a low value of $\rho_0$.

**Nature of dark matter**

From the preceding discussion there is associated with some single galaxies and small groups of galaxies an amount of dark matter, in some cases exceeding the luminous matter in mass, and this is probably largely baryonic.

On the model its chemical composition must be roughly what we regard as cosmical. This material cannot be in the form of gas and dust because matter in such a state would either disperse or form condensations held together by self-gravitation. Since it has not dispersed and since it is dark, it must be in the form of "sub-stellar" bodies. On general grounds we should expect them to be sub-stellar by only a small margin i.e. not a great deal smaller than about 0.1 solar mass. Let us call these "jupiters". They would be moving freely in the gravitation field of the system to which they belong. Once such a system had been established in a volume of the expected size it would be effectively non-dissipative i.e. permanent.

We have seen in the previous section that a large enough mean matter-density in the present Universe would probably demand the existence of a
non-baryonic contribution. We have not found scope to discuss another parameter, the mass: light ratio for a system of galaxies. Schramm (1982) claims that if this ratio approaches about 100 times the value for the Sun, then the mass could not be wholly baryonic. It is only in large clusters of galaxies that values as large as this are suggested by some observations.

Thus in the present state of knowledge we cannot assert that any actual observation positively requires the existence of a considerable non-baryonic mass-contribution; nor are we able to say that observations rule it out.

The only energy known to exist in the Universe that is not in the form of baryonic matter nor electromagnetic is in the form of neutrinos. On the standard model these pervade the Universe with a large number density.

But according to all generally accepted physics they are of zero rest-mass, and they become decoupled from other contents of the Universe about 0.1 second after the big-bang, playing no significant role thereafter. However, it is well known that in the past few years there has been much renewed interest in the possibility of the neutrino possessing non-zero rest mass and some experimenters have claimed to have measured it. Even if this mass were as small as the equivalent of an energy of only 1.5eV it is estimated that the Universe would be neutrino-dominated. In the present context the main interest is that all the neutrinos liberated at the epoch of neutrino decoupling would have suffered the corresponding enormous red-shift in total energy. They would now be moving quite slowly and it is easy to calculate that they could form a gravitational condensation around a large cluster of galaxies. Calculation shows also that they would be unlikely to form a condensation around a group of only a few galaxies. Thus if non-baryonic mass is needed by large clusters and not by others, “massive” neutrinos are the most natural source yet proposed. Also this would support the existence of neutrino rest-mass.

Nevertheless, it has to be emphasized on the one hand that cosmology makes no undoubted demand for non-baryonic mass and on the other hand that laboratory experiments have not yet convinced most physicists that neutrinos do possess non-zero rest mass. It should just be mentioned that suggestions have been offered about black holes and about “exotic” particles, e.g. gravitinos, photinos, that might supply non-baryonic mass, but without evident profit.

Condensations in cosmology

The observed Universe appears to be in the large isotropic about ourse-
ves, and presumably also about any other co-moving observer, to a high degree of accuracy. It is then usually inferred that a cosmological model that reproduces this state of affairs for our cosmic time must in its earliest stages have been isotropic about any co-moving observer to some quite fantastic degree of accuracy.

In passing we should recall the difficulty of this concept.

In such a model in general any co-moving observer sees contents entering his range of observation through a horizon. When he first sees any such contents in, say, directions on opposite sides of himself he sees two lots of contents in states in which they could not yet have had any influence upon each other. Nevertheless, these states have to be in effect perfectly matched in order to produce the required isotropy. The so called “inflationary universe” is claimed to ameliorate this difficulty.

But I cannot see how it can be wholly overcome unless we require the model to have no effective horizon.

There is another difficulty as well. The high degree of isotropy in the early universe - in the model - implies a corresponding high degree of homogeneity. If the universe is homogeneous, there is nothing in it that can disturb its homogeneity, and so condensations could never form. We know very well that there are condensations - galaxies, etc. - in the actual universe. We infer that there must therefore always have been condensations, and that it is meaningless to ask what caused the first ones. Thus the universe could never have been truly homogeneous, and we appear to have a fundamental contradiction.

Some years ago there appeared to be a way out of this difficulty.

It was suggested that the Universe might have started more or less anyhow and that neutrino viscosity and radiation viscosity in the very early stages would have achieved a sufficient degree of homogeneity but with also sufficient imperfection to ensure that there were indeed always some irregularities. The basic idea of this approach was due to C. Misner, but it is now thought that the suggested processes for ensuring adequate homogeneity of the Universe in the large would not be effectual.

In reporting about cosmology today it seems fair to say that cosmologists for the most part have laid aside the problem of the root cause of fluctuations. Instead they postulate that there were fluctuations of one sort or another - those classed as “isothermal” or as “adiabatic” - just prior to decoupling, and proceed to study their subsequent evolution.

The motivation is apparently that if one sort of fluctuation leads more successfully than any other to galaxy-formation then that should be the sort for which in due course we hope to find a cause.
It is not feasible here to describe such work in general. In the following section I sketch a particular simplified model that may at least indicate some of the essential features of the problem.

**Galaxy formation**

Here I wish to mention what appear, in the present context, to be the main features of a model of galaxy formation that I have tried to present in recent years (McCrea 1979, 1982, 1983).

In the expanding universe, directly after decoupling, the still uniform matter starts cooling quite rapidly. The first consequence is here taken to be a fragmentation of the material into portions ("clouds") of all sizes. This is the present version of the postulation of some sort of fluctuation mentioned at the end of the previous section. The system as a whole must continue to expand. But some neighbouring clouds will fall together under their mutual gravitation. The only disposable parameter is the mean density of the material $\rho$ at the start of the proceedings. In a case of present interest the encounter would be supersonic, and it would produce a layer of shocked material which would have temperature $T_d$. The defining property of $T_d$ requires this to tend to happen. If it does not do so sufficiently rapidly, the case simply ceases to be of present interest; on the model this may be the essential factor in setting an upper bound to the mass of a resulting galaxy. It is found to be a fairly general result that the resulting layer would be gravitationally unstable in such a way as to break up into "Jeans condensations" (primary condensations) of diameter about the thickness of the layer. All such condensations formed in an encounter would be gravitationally bound as an aggregate and would proceed to move around under their mutual gravitation as a permanent aggregate.

At the same time each individual primary condensation would proceed to collapse upon itself, initially under effectively free fall. I infer that this yields one or more supermassive stars that will explode about the time when the infall is well advanced. The material has "primordial" composition to begin with and the career and subsequent explosion of a massive star would produce heavier atomic nuclei to enrich any remaining raw material. The explosion would result also in producing shocks in this material and qualitatively the sort of conditions in which normal stars are now believed to form in, say, the spiral arms of our Galaxy. Thus I take it that each primary condensation produces a globular cluster of stars, or an equivalent number of stars dispersed into the system as a whole. The system as a whole I take naturally to be a ga-
laxy in the model. If the original encounter was effectively face-on the galaxy would be formed without much resultant angular momentum, and it would be classed as “elliptical”. If the encounter was “shearing”, the galaxy would have considerable angular momentum and it would presumably be a “spiral”.

By way of illustration I have considered the case of $\rho$ corresponding to one hydrogen atom per cubic centimetre. Then I find that if the encountering clouds have “galactic” masses, the resulting system is indeed like a galaxy - the globular clusters have about the right mass, and the system as a whole has about the right size.

The model seems to have obvious merits. It produces globular clusters in producing a galaxy and it produces the first heavy elements exactly where they are needed in order to produce the first normal stars.

According to the model the cloud-masses may have any value. An encounter between clouds of small mass would produce nothing interesting.

A cloud of large mass could encounter several smaller ones about the same time, and so produce a group of galaxies. The model would be expected not to produce a large cluster in the same way. But this may be in accordance with some current thinking on the subject which views such clusters as being formed by some process of merging smaller groupings.

One possible outcome is of special interest in the context of this paper. On the model, the oldest stars in a galaxy are the first normal stars formed in potential globular clusters. The clusters may be dispersed in process of formation, or later by tidal action, so that these stars become the “halo” population of the resulting galaxy. Now I have given reasons (McCrea 1983) for inferring that the mean mass of such stars would be expected to be proportional to $M^{-1/3}$, where $M$ is the mass of the galaxy concerned.

Thus, if in a fairly normal galaxy the halo stars average about $\frac{1}{2}$ solar mass, which seems plausible, then the halo stars for a system of say 100 times the mass would average little more than 1/10 solar mass. Therefore on average they would be dark bodies. This would provide a quite likely amount of dark matter in bodies of the expected sort and distributed through the volume where such mass is inferred to exist in relevant cases. As we have seen, once formed such a system would be long-lived.

Much more detailed study is required adequately to develop such a model. Here we are mainly concerned to show that, provided some agency can be identified that can trigger some sort of fragmentation or condensation of the matter in the universe not long after the epoch of decoupling, then something generally like actual galaxies seem bound to result - even to the extent of pos-
sibly including a considerable amount of dark matter.

Discussion

This rather fragmentary review tends to show that:

1) Standard big-bang cosmology provides an acceptable account of the history of the Universe from about the first second up to the epoch of decoupling of radiation and matter.

2) Given some triggering of condensation soon after that epoch, such cosmology seems to be capable of accounting for the existence of galaxies in satisfactory accord with observation.

Aspects of the Universe that are not yet satisfactorily treated are:

1) The very early universe and in particular the explanation of the value of the parameter \( \eta \).

2) More generally the justification of any concept of a big-bang i.e. of phenomena that are essentially unobservable.

3) The triggering mechanism of the "first" condensations, presumably about the epoch of decoupling.

4) The whole question of why physical constants exist and why they have the values they do. This is part of cosmology because if we study the origin of the physical Universe part of the problem is the origin of its constants. Also it is often remarked that had the values of some of the constants been only a little different, the whole Universe would have been altogether different, and in particular beings like ourselves could not have evolved in it.

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