THE ROLE OF PARTICLE PHYSICS IN COSMOLOGY AND GALACTIC ASTRONOMY

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ABSTRACT

A non-technical introduction is given to (a) the inflationary universe, (b) the production of baryon asymmetry by GUTs, (c) the possible role of massive neutrinos and (d) the possible role of the massive photinos and goldstinos of broken supersymmetric theories.

INTRODUCTION

The organizers have asked me, in this final lecture, not to summarize the Symposium but to give a broad review for astronomers of the role of particle physics in cosmology and galactic astronomy. Recent developments have shown that the possibilities here are very great, and that many observable features of the universe, and even of galaxies including our own, may have their origin either in processes occurring extremely close to the big bang, say within 10^{-35} seconds; or in effects arising from the most recent developments in particle physics, such as Grand Unified Theories (GUTs) and supersymmetry. All these matters are still very speculative. Nevertheless, I believe that the time has now come for astronomers to take these possibilities seriously, and clearly our organizers feel the same way! One problem is that modern particle physics and quantum field theory are highly elaborate and technical subjects which do not lend themselves to simple exposition. In consequence, most astrophysicists are unfamiliar with them. On the other hand, most particle physicists do not know the intricacies of modern astrophysics. Nature herself faces no such problems, of course, and all one can do is to stumble hopefully in her wake. This review is written in the further hope that it will encourage more astronomers to join the stumblers.

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QUANTUM GRAVITY

The quantum gravity epoch presumably occurred at the Planck time $(hG/c^5)^{1/2} \sim 10^{-43}$ seconds. Unfortunately, not much progress has been made recently in finding a satisfactory quantum theory of the gravitational field (see, for example, Isham, Penrose and Sciama 1981). Many people now pin their hopes on supergravity and its unification with particle theories such as GUTs. Severe technical problems still remain to be solved in this programme, however, and the outcome is not clear. For the astronomer the importance of quantum gravity is that (a) it may eliminate the classical singularity at $t = 0$, thereby leading to a clearer view of the initial conditions in the hot big bang; (b) it may lead to the formation of particle-antiparticle pairs of various species, whose annihilation could have provided the initial heat needed to generate the hot big bang; (c) the same pair production process might have equalized the expansion rates of the universe in different directions, so accounting, in part, at least, for the presently observed high isotropy of the Hubble constant and of the 3°K background.

I think that it is fair to say that not much progress has been made with these problems in recent times. This is in strong contrast to the remaining topics in this review, all of which have been transformed, or even come into existence, in the last few years.

THE INFLATIONARY UNIVERSE

This refers to a remarkable scheme designed to solve the so-called horizon and flatness problems (although, of course, whether the scheme is really valid should be decided eventually from first principles). Let us begin by considering what these problems are.

The Horizon Problem

The 3°K background is observed to be isotropic to better than 1 part in 10^3, yet, according to standard theory, if one looks at the background in opposite directions the points observed on its last scattering surface would lie nearly one hundred horizon lengths apart (one horizon length corresponding to the largest region in causal contact with itself in terms of processes propagating with the speed of light). Thus, there would not have been time for transport processes to even out the temperature over the whole of the last scattering surface, even if they had started operating close to the big bang itself. It follows that either the rather precise equality of temperatures was imposed as an initial condition in the big bang, or some non-standard mechanism intervened to enlarge the horizon or to eliminate it. As we shall see, the inflationary universe could provide such an enlargement mechanism.

The Flatness Problem

The mean density of the universe to-day is probably within a factor of ten of the critical density. An exact equality of these densities would represent a sort of equilibrium point for Robertson-Walker models in the sense that this equality would then hold at all times (Einstein-de Sitter model). But this equilibrium is unstable in the sense that a deviation between the two densities would increase with time. For example, if the present density were one tenth of the critical value, then at a temperature of 1 Mev it would have been within one part in 10^5 of critical, while at a temperature of 10^{14} Gev it would have been within one part in 10^{49}. Such"fining tuning"looks unnatural, and suggests that either the density is indeed exactly critical, for a reason still to be discovered, or that some non-standard mechanism intervened to drive the present value of the density close to the critical value. Again, we shall see that the inflationary universe claims to provide such a mechanism.

To see what would be involved in a solution to the flatness problem, let us take a look at the standard Friedmann equation for an expanding universe

$$H^2 = \frac{\dot{R}^2}{R^2} = \frac{8\pi G\rho}{3} - \frac{k}{R^2} \tag{1}$$

in the usual notation. If the curvature k were zero, we would have the Einstein-de Sitter model with

$$\frac{8\pi}{3} \frac{G\rho_c}{H^2} = 1 \quad ,$$

giving the critical density ρ_c in terms of the Hubble constant H. In the radiation dominated case, which has

$$\rho \propto T^4 \propto \frac{1}{R^4} \quad ,$$

the resulting differential equation for R is trivial to solve and yields

$$R \propto t^{1/2} \ .$$

Now, our present task is to prevent the k term in (1) from unduly dominating the ρ term for large R (note that the present epoch corresponds to about 10^{60} Planck times - the Planck time being the only natural time scale defined in a radiation dominated universe). However, in the standard theory precisely the opposite occurs, that is, the k term is suppressed at small R. This familiar result arises because, with $\rho \propto 1/R^4$ and the k term $\propto 1/R^2$, clearly the ρ term must dominate for sufficiently small R. This is the basis for the usual discussion of a radiation dominated universe near $t = 0$.

How then can we arrange for the k term to be small, or at least not unduly large, at large R? A brilliant answer to this question occurred to Guth in 1981. We shall approach his idea in a number of steps, drawing on our knowledge of the byways of cosmology, of which Guth tells me he was unaware. Some of us remember the steady state theory of the universe and in particular Hoyle's(1948) discussion of how the steady state could be reached asymptotically in the future, that is, for large R, under the driving action of the "C field". This is relevant to our discussion, because the asymptotic steady state (which in fact corresponds to the de Sitter form

$$R \propto e^{Ht}) \quad ,$$

indeed has a negligible k term, as we would require. The driving mechanism is based on the C field which, roughly speaking, has a constant energy density ρ_0 given by

$$8\pi G \rho_0 = \lambda \quad ,$$

where λ can be interpreted alternatively as the cosmical constant. A glance at (1) shows that with this part of ρ now independent of R, the k term does indeed become negligible at large R. When it is negligible the differential equation is again easy to solve, and one obtains the exponential form characteristic of the de Sitter metric. If the ρ and k terms start out comparable, then the asymptotic form is accurately reproduced in a few expansion time-scales $1/H$, owing to the tendency of the scale factor R to increase exponentially fast.

A second reason for thinking that the steady state theory may be relevant to our problems is that an exactly de Sitter universe would have no particle horizon at all. This difference from the usual case has to do with the very different behaviours of R for small t in the exponential form, where it tends to a constant, and in algebraic forms like $t^{1/2}$, where it tends to zero.

We can thus try introducing a new idea which might solve both the flatness and the horizon problems. If there had been an early stretch of approximately steady state behaviour, say for 100 Hubble times, then R would have been inflated by e^{100}, the k term would have been suppressed by a large factor, unless it had originally been extremely dominant, and the horizon might become enlarged sufficiently to permit the causal propagation of transport processes across the presently observable universe.

The difficulty with this idea is giving the steady state stretch a sound physical foundation. The weak point of Hoyle's proposal (apart from the accumulating observational evidence against the steady state theory) was that his C field was introduced in an ad hoc manner, unrelated to basic physical theory. Of course, Hoyle was ahead of his time - Guth's proposal for interpreting the λ term as an energy density is based on GUTs, and came 33 years later!

Guth's basic idea is that a so-called false vacuum would have an energy density of this form. Let us first try and understand what a false vacuum is. A good analogy, often cited, is with a ferromagnet. Above its Curie temperature a ferromagnet, free of an external magnetic field, would have zero net magnetic moment - the directions of its spins would have no long-range order. As its temperature is lowered, a phase change occurs when the system passes through its Curie point. At this critical temperature a change of symmetry occurs, with the spins tending to line up in an ordered way, thereby giving the ferromagnet a net magnetic moment. This change of symmetry corresponds to a loss of isotropy - the spins choose a particular spatial direction in which to point. However, this loss of symmetry is only partial, in the sense that the energy of the system would be the same whatever the overall direction chosen by the spins (in the absence of an external magnetic field). Thus the actual direction chosen in any particular case has to do with the detailed history of that specimen and has no fundamental significance; isotropy is still present.

The final feature of this analogy which we shall need is that below the Curie point the unmagnetized state possesses more energy than the magnetized one. Indeed, that is why the transition to the magnetized state takes place. However, while the temperature is being lowered through the Curie point, supercooling may occur, with a consequent delay in the onset of the phase transition. The supercooled phase would then have an excess energy and this, as we shall see, is analogous to the energy of the false vacuum in Guth's hypothesis.

We now return to GUTs. These are generalizations of the electroweak theory (which unified the electromagnetic and weak interactions) involving also the strong interactions. (For technical accounts of these theories see Langacker (1981) and Ellis (1981)). At high temperatures the lowest energy state of the fields is highly symmetrical (like the unmagnetized state of a ferromagnet, which defines no preferred direction in space). As the temperature is lowered through a critical value ($\sim 10^{14}$ Gev) a phase change occurs in which the fields lose their high symmetry, in a manner analogous to the ferromagnet, that is, by choosing one amongst an infinite number of states of the same energy in an "accidental" way; each of these states defining a preferred direction in an abstract space associated with the basic fields of the theory. It seems likely that this phase change is of the first order(that is, possesses a latent heat) in which case supercooling would be expected to occur. Of course, in the application of these ideas which Guth has in mind, the reduction of the temperature is associated with the expansion of the universe, and the supercooling would persist for a time determined by kinetic considerations. When the supercooling terminates and the system makes a transition from the false vacuum to the true vacuum, the latent heat is released, thereby increasing the entropy of the universe. According to current calculations this entropy increase is very considerable, and should be expected to be responsible for the major part of the present $3^{\circ}K$ radiation background.

Guth's idea is that the energy density of the supercooled phase would have the form of a λ term which drives a "steady state stretch" for the duration of this phase. The existence of this stretch could then solve the horizon and flatness problems in the manner which we have already indicated. Guth's idea is widely regarded as highly plausible, but I must emphasize that it depends on an aspect of the theory which is not at all well understood. To see what is involved let us first consider the true vacuum state at temperatures below the critical value of 10^{14} Gev. This state picks out a preferred direction in the abstract space, but is not expected to do so in physical space-time. Accordingly, the energy momentum tensor $T_{\mu\nu}$ of this state must have the form $\lambda g_{\mu\nu}$, where $g_{\mu\nu}$ is the metric tensor and λ is a constant. This has just the same form as a cosmical term in Einstein's field equations. However, in the universe to-day, the cosmical constant is observed to be many powers of ten smaller than any "natural" value it might have in a GUT theory (other than zero). It is therefore presumed that either the present GUT value of λ is strictly zero, or some cancellation mechanism exists (perhaps related to further symmetry considerations) which ensures that the total value of λ is zero.

The idea then is that any cancellation mechanism gets "used up" in this way, so that since the false vacuum in the supercooled phase has higher energy than the true vacuum, this excess energy survives and is physically real. This real energy would also have the form of a λ term, and would be expected to have a GUT-like value (corresponding, say, to an energy density $\sim T^4$ with $T \sim 10^{14}$ Gev). This assumption, and the related question of the present value of the cosmical constant from a field-theoretic point of view are the least understood parts of Guth's ideas, and constitute perhaps the most important unsolved problems in the relationship of gravitation to the other forces of nature.

If we accept this reasoning, we can use the λ term from the supercooled phase to generate a stretch of approximately de Sitter type exponential expansion in which the k term becomes highly suppressed and the extent of the horizon grows considerably. The duration of this stretch, and the details of the transition from the false vacuum to the true one, depend on uncertain parameters of the GUT theory involved. In Guth's original version the transition occurred sporadically in small bubbles which later collided in a complicated way. This led to a number of difficulties. In the new version, the symmetry change at the phase transition is ascribed to a different mechanism (it is induced by so-called radiative corrections, in a manner first proposed by Coleman and Weinberg (1973)). This would eliminate many of the difficulties. In particular, the whole of our observable universe would now fall well inside a single bubble. Apart from eliminating the collision problem, this would have the advantage of avoiding an embarassingly large flux of magnetic monopoles which would be associated with bubble walls.

This improved version was discussed in great detail at a Workshop organized in Cambridge this summer by G.W. Gibbons and S.W. Hawking, the proceedings of which will be published by the Cambridge University Press. The general consensus at the Workshop was that the new version represents an important step forwards, but that the assumptions leading to the Coleman-Weinberg form of the potential involve too much fine tuning. A more natural theory is still needed. The possibilities here are wide open. For instance, the inflation might have occurred during the quantum gravity phase at the Planck time, or it might involve supersymmetry (a theory which we shall discuss later on). A further problem is that irregularities arising during the supercooled phase, which might later lead to galaxy formation, for the moment seem to be embarassingly large.

I have tried to keep a fair balance by highlighting the difficulties, but in my opinion, and that of many people at the Workshop, they are the kind of difficulties which we could reasonably expect to be resolved by new ideas. Their existence should not blind us to the remarkable potential of the inflationary hypothesis, which at a stroke could solve both the flatness and horizon problems, and provide us with a new conception of the large scale structure of the universe. Moreover it would change our attitude to the role of initial conditions in accounting for the present state of the universe. The reason for this is that, as we have already seen, when the false vacuum decays, its energy, as represented by the λ term, is released as latent heat. This heat would correspond to a black body radiation field at a temperature $\sim 10^{14}$ Gev, whereas when this heat is released the universe would have supercooled down to a much lower temperature, say 10^{8} Gev. Thus, very considerable reheating occurs and the universe would be "born again". In particular, as we have already mentioned, the 3^{o}K background which we observe today, would have its main origin in this reheating.

I stress this last point, not only for its intrinsic interest to astronomers, but also because the restoration of a temperature of 10^{14} Gev would permit the operation of another GUT mechanism, which has been widely invoked to account for the presumed baryon asymmetry of the universe, and for the presently observed value of the ratio of baryon number to the photon number in the 3^{o}K background. To this mechanism we now turn.

THE PRODUCTION OF BARYON ASYMMETRY IN THE UNIVERSE

We begin with the assumption that the universe at very high temperatures was baryon symmetric, with equal numbers of baryons and anti-baryons being thermally excited. As the universe cooled it is supposed that reactions occurred which led to the production of $1 + \varepsilon$ baryons for every anti-baryon. Eventually, the baryons and anti-baryons annihilated into photons, leaving of order ε baryons for every photon. Since at high temperatures the number of baryon pairs in thermal

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equilibrium would be of the same order as the number of photons, this would mean that today's value of n_b/n_γ would be of order ε. Thus, if $\varepsilon \sim 10^{-10} - 10^{9}$, we would have accounted for the observed number of baryons per photon in terms of the microscopic processes which determine ε.

An essential feature of this mechanism is that baryon number is not conserved (by a relative amount measured by the small quantity ε). Until recently, in particle physics baryon number was thought to be absolutely conserved, although it was recognized that this conservation law was on a less fundamental footing than, say, the conservation of charge. However, in the unification achieved by GUTs strongly interacting quarks and electroweak leptons are placed essentially on the same footing. Since baryons are made up of quarks, there would be no absolute barrier to their decay into leptons. The half-life of a proton, for example, turns out to be of order m_X^4/m_p^5, where m_X is the mass of the X boson which mediates the grand unified interaction. This mass is believed to be about 10^{14} Gev. (This is the characteristic energy scale for GUTs, at which, for example, strong, electromagnetic and weak coupling constants all have the same value.) The predicted half-life is thus about 10^{31} years. The present experimental lower limit is about 3×10^{30} years. There are a number of experiments now under way looking for proton decay. A few potential events have been found, but the consensus at the recent Paris meeting on elementary particle physics was that nothing definite can be said as yet, although the situation should be much clearer in a year's time.

Following an original analysis by Sakharov, various people have suggested that the X boson of GUTs could be used to produce a baryon asymmetry. In rough outline what is proposed is as follows (for a more careful,but still fairly general, discussion, see Weinberg (1982)). At temperatures in the early universe above 10^{14} Gev thermal equilibrium is expected to have prevailed, with equal numbers of baryons and anti-baryons, and of X and $\bar{X}$ being present. When the temperature dropped below 10^{14} Gev, there was insufficient thermal energy to replace the X and $\bar{X}$ which disappear by decaying into B and $\bar{B}$, but with $B = (1 + \varepsilon)\,\bar{B}$. (This imbalance is a consequence of the CP non-invariance of the X boson's interactions.) As we have seen, this imbalance could then account for the present baryon asymmetry if $\varepsilon \sim 10^{-9} - 10^{-10}$. Attempts to calculate ε in detail have not led to very definite results, but a value of this order certainly falls within the range of possibilities.

So far I have described this idea as it was originally proposed, before Guth's inflationary universe had been introduced. In Guth's scheme the re-heating produced when the false vacuum decayed was so extensive that it would have reduced the prevailing baryon photon ratio to utterly negligible proportions. It is therefore an important feature of this scheme that after the re-heating the temperature was restored to 10^{14} Gev, so that the baryon asymmetry mechanism as described above could have then come into operation.

IMPLICATIONS OF NEUTRINO MASSES

Since many varieties of GUT, except admittedly the simplest one, lead to non-zero rest masses for neutrinos, it seems appropriate to consider here the possible role of such neutrinos in cosmology and galactic astronomy. I reviewed this subject at the recent Vatican conference, the proceedings of which have now been published (Sciama 1982a) and have reported on the ultraviolet aspects elsewhere in this symposium (1983). I will therefore be brief and will concentrate mainly on some recent developments.

We can link up this discussion with our earlier considerations by following Guth in his conclusion that the universe today possesses essentially the critical density. If we further assume that $\lambda = 0$, then the universe must be close to the Einstein-de Sitter form, and astronomical estimates of its age would indicate that the Hubble constant must be close to 50 km.sec.$^{-1}$ Mpc^{-1} (corresponding to an age $\sim 13 \times 10^9$ years).

To determine the contribution of massive neutrinos to the density of the universe we note that at high temperatures they would have been in thermal equilibrium, through weak interactions of the type $\nu + \bar{\nu} \leftrightarrow e^- + e^+$. For left-handed Majorana neutrinos these interactions become too slow to maintain equilibrium when the temperature has dropped to $\sim$ 1-3 Mev, at which time the neutrinos would have become decoupled. This detail is important because electron pairs permanently annihilate somewhat later (at $T \sim 1/2$ Mev), so that the resulting photons would have fed the 3°K background, but not the neutrinos. As a result, if the neutrinos were relativistic at decoupling, their present concentration n_ν would be suppressed below that of the photon concentration in the 3°K background ($\sim$ 400 cm^{-3}) by a factor of order 4. If the neutrinos were non-relativistic at decoupling ($m_\nu C^2 > kT_d$) they would be further suppressed by previous annihilation, but we shall not consider this case here. In summary, for $m_\nu < 1$.Mev we would have for each neutrino type

$$n_\nu \sim 100 \text{ cm}^{-3} .$$

If the neutrinos are essentially responsible for the critical density we would then require that

$$\sum m_\nu \sim 25 \text{ eV} \quad , \tag{2}$$

where the sum is over the different neutrino types. In practice, of course, one type (the tau neutrino?) might be much more massive than the others.

It is well known that the number of types N_ν, which were relativistic at decoupling is constrained by observations of the abundances of D, He^3, He^4 and Li^7 in comparison with the results of

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nucleosynthesis calculations for the hot big bang. The recent tendency has been for this constraint to become more stringent, and it is now widely considered that $N_\nu < 4$ (e.g. Barrow and Morgan (1982)). Since three neutrino types are already known (although the tau neutrino might be too massive to have been relativistic at decoupling) this is a remarkable result. We shall use it with greater force when we come to consider the photinos of supersymmetric theories in the next section.

It has been widely conjectured that such massive neutrinos might dominate galactic halos as well as the whole universe. A key role would be played here by the Liouville theorem, which would apply to neutrinos after decoupling (Tremaine and Gunn 1979). This theorem requires their phase space density following the motion to be constant in time, or if phase mixing is important in some process of violent relaxation, to be decreasing. Accordingly, their density ρ_ν in the galaxy today would have to be bounded as follows:

$$\rho_\nu \le \rho_Q = \left(\frac{2\pi}{3}\right)^{3/2} \frac{m_\nu^4 v_0^3}{h^3} ,$$

where m_ν is the mass of one neutrino type, v_0 is its three-dimensional velocity dispersion (assuming a gaussian distribution) and h is Planck's constant. For example, if $m_\nu = 100$ eV and $v_0 = 100$ km $\sec^{-1}$, then $\rho_Q = 10^{-24}$ gm. cm^{-3}, which turns out to be a typical galactic density.

Following Caldwell and Ostriker (1981) we might model the galactic halo by

$$\rho = \frac{\rho_0}{1 + \left(\frac{r}{a}\right)^2} .$$

This would yield the desired flat rotation curve for $r \gg a$, but would allow for the gravitational influence of stars and gas for $r \lesssim a$. Their preferred galactic model then has

$$\rho_0 = 10^{-24} \text{ gm. cm}^{-3} ,$$

with an uncertainty of about a factor 2, and

$$a = 7.8 \text{ k pc} .$$

It is tempting to identify the required cut-off in the increase of ρ at small r with the approach of the neutrino density to the maximum permitted value ρ_Q. If we further assume that v_0 is independent of

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r, then its value is determined from the circular velocity v_c of the outer halo by $v_0 = \sqrt{3/2}\, v_c$. If we take $v_c \sim 220$ km sec^{-1}, we would have $v_0 \sim 270$ km sec^{-1}. The assumption that $\rho_0 = \rho_Q$ then leads to

$$m_\nu \sim 45 \text{ eV} \quad ,$$

assuming for simplicity that the mass of one neutrino type is dominant.

It is not quite clear whether this represents good agreement with (2) or whether the discrepancy of a factor ~ 2 should be taken seriously. We are, of course, assuming that phase mixing has not reduced appreciably the phase space density in the central regions of the galaxy; otherwise the discrepancy would be increased. However, Melott's (1982a,b) numerical simulations of neutrino collapse do suggest that the phase density is not much reduced in the central regions of the collapsed system.

In view of all the uncertainties, one should perhaps regard the two mass estimates, which are completely independent, as in remarkable agreement. However, the speculation (Sciama and Melott 1982), described in my other article in these proceedings, that photons emitted by galactic neutrinos are responsible for the high ionization stages represented in the galactic halo (and in the halos of other galaxies) by Si IV and CIV would require that $m_\nu \sim 100$ eV. This further increase of mass would correspond to a definite discrepancy and would lead to problems with the age of the universe (if $\lambda = 0$). These problems, however, could be relieved by replacing neutrinos with photinos, as we shall now see.

SUPERSYMMETRY AND MASSIVE PHOTINOS

GUTs do not yet lie at the end of the road, according to most particle physicists. This is partly because they still contain a large number of undetermined quantities, and partly because they present particular problems, such as the famous hierarchy problem: why are the important masses so widely spaced out, e.g. at 100 Gev (electroweak gauge particles, the W and Z bosons), 10^{14} Gev (the X bosons of GUTs), and 10^{19} Gev (the Planck mass)? This is particularly puzzling because one would expect interactions to drag, say, the masses of the 100 Gev bosons up to 10^{14} Gev, unless a miraculous cancellation occurs to many places of decimals - the fine tuning problem again.

In supersymmetric theories (for a technical review see Fayet and Ferrara (1977)) this miracle can occur by virtue of the supersymmetry itself. This new symmetry (which is the only one left unexploited by existing gauge theories) has the remarkable property of interrelating bosons and fermions, which thereby can occupy the same multiplet of particles. Thus, if supersymmetry were an exact symmetry, the electron, for example, would have a scalar partner of the same mass. Such a particle is known not to exist, and so one would have to suppose that in

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the real world the supersymmetry is broken, just as the GUT symmetry is broken at energies below 10^{14} Gev. The scalar partner of the electron could then have a much higher mass which could leave it unobservable at present. The energy at which supersymmetry is broken is not known, although we shall see that cosmology may provide some clues both to this and to other parameters of supersymmetric theories.

For our purposes the important new particles thrown up by supersymmetry are the photino, which is the spin 1/2 partner of the photon, and the goldstino, a spin 1/2 particle related to the breaking of the supersymmetry. These particles are important for at least two reasons. First of all they may have been sufficiently numerous when the temperature of the universe was 1 Mev to influence the time scale of the expansion and so the outcome of nucleosynthesis. Secondly, if they have masses of order tens or hundreds of electron volts, they could replace massive neutrinos in regard to the critical density for the universe, the dark matter in galactic halos, and the emission of ultraviolet photons.

These considerations are highly speculative, since there is as yet no experimental evidence in favour of supersymmetry. Nevertheless, the possibilities are intriguing, particularly because the argument goes both ways, that is, while aspects of supersymmetry would be important for cosmology, cosmological constraints would be important for supersymmetry. For example, if we are allowed only a fraction of an extra "neutrino type" by the nucleosynthesis argument, this could be achieved by supposing that photinos and goldstinos decoupled before muons and pions annihilated, since this would result in their further suppression relative to photons in the $3^{o}K$ background. Such a decoupling requirement would have strong implications for the coupling constants of supersymmetric theories, and for their structural features generally (such as their capacity to solve the hierarchy problem) (Sciama 1982c). In addition the resulting suppression of the photino number density would permit 100 eV photinos to provide the critical density without running into an age problem for the universe (Sciama 1982b).

CONCLUSIONS

The reader may be appalled by the amount of speculation in this article. All I can say in my defence is that I find it hard to believe that it is all wrong and/or misleading. Even if only a small part of it is found to be on the right lines, we would still be witnessing the birth of imaginative new possibilities for our understanding of the universe, which will presumably leave their permanent mark on the growth of this understanding.

REFERENCES

Barrow, J.D. and Morgan, J.: 1982, to be published.

Bruck, H.A., Coyne, G.V. and Longair, M.S., Eds.: 1982, Astrophysical Cosmology, Pontifical Academy of Sciences.

Caldwell, J.A.R. and Ostriker, J.P.: 1981, Ap.J. 251, 61.

Coleman, S. and Weinberg, E.J.L 1973, Phys.Rev. D 1888.

Ellis, J.R.: 1981, Les Houches Summer School.

Fayet, P. and Ferrara, S.: 1977, Phys.Reps. 32C, 249.

Gibbons, G.W. and Hawking, S.W., Eds.: 1983, Cambridge Workshop on the Very Early Universe, Cambridge Unversity Press.

Guth, A.H.: 1981, Phys.Rev. D23, 347.

Hoyle, F.: 1948, Mon.Not.Roy.Astr.Soc. 108, 372.

Isham, C.J., Penrose, R. and Sciama, D.W., Eds.: 1981, Quantum Gravity 2; a Second Oxford Symposium, Oxford University Press.

Langacker, P.: 1981, Phys.Reps. 72, 185.

Melott, A.L.: 1982a, Phys.Rev.Lett. 48, 894; 1982b, Nature 296, 721.

Sciama, D.W.: 1982a, in Astrophysical Cosmology, Eds. Bruck, H.A., Coyne, G.V. and Longair, M.S., Pontifical Academy of Sciences, p.528; 1982b, Phys.Lett. 114 B, 19; 1982c, Phys.Lett. to be published; 1983, these Proceedings.

Sciama, D.W. and Melott, A.L.: 1982, Phys.Rev. D25, 2214.

Tremaine, S. and Gunn, J.E.: 1979, Phys.Rev.Lett. 42, 407.

Weinberg,S.: 1982, in Astrophysical Cosmology, Eds. Bruck, H.A., Coyne, G.V. and Longair, M.S., Pontifical Academy of Sciences, p.503.

Discussion

Schmidt: You stated that massive neutrinos could provide the Oort dark matter near the sun. Would they, in fact, provide all of it, or only part of it?

Sciama: They could provide all of it if neutrinos of low velocity dispersion form a thin disk, while those of higher velocity dispersion form a quasi-spherical halo. The total column density of neutrinos would be fixed by the observed rotation velocity of the galaxy. The phase space density constraint applied to the thin disk would then require the neutrinos (or, better, photinos) to have a higher rest-mass than is normally considered, say, 100 - 250 eV. This would be compatible with the critical density if the photinos were sufficiently suppressed by becoming decoupled sufficiently early, say, at a temperature $\sim$ 200 MeV.

McCrea: Why is there any ordinary matter? Why is the universe not <u>all</u> neutrinos? Do we exist simply because $\varepsilon \neq 0$?

Sciama: The ordinary matter which now exists arises, according to the theory I outlined in my talk, from the slight excess, ε, of baryons over antibaryons when X-bosons decay at a temperature $\sim 10^{14}$ GeV. Thus, on this view we do indeed simply exist because $\varepsilon \neq 0$ (and because galaxies, stars, planets, etc., came into being!).

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Peacock: If we accept all this, then what do you see as the fundamental remaining cosmological problems?

Sciama: The audience can answer this as well as I can! Some problems which clearly remain are: the origin of galaxies, whether the universe is open or closed, how to deal with the initial singularity, etc., etc. We shall clearly need at least one more IAU symposium on cosmology.

Code: Apparently massive neutrinos or photinos can play similar roles in the cosmological scenario. Thus, either one or perhaps both are operative. You must, therefore, mean that you can provide some constraints or limits on the photino coupling constants from astrophysics and not a determination of the coupling constants.

Sciama: The photino coupling constant is constrained by the requirement that photinos decouple sufficiently early in the big bang that their number-density is suppressed relative to that of neutrinos. This suppression is required a) by the upper limit on the number of particle types permitted by the big bang nucleosynthesis argument and b) by the upper limit on the photino mass-density imposed by the age of the universe. Of course, this second limit depends on the rest-mass of the photino, for which only indirect arguments (both astronomical and from particle physics) exist at the moment.

G. Ellis: Is there some form of energy non-conservation during the exponential phase of the universe's expansion?

Sciama: There is no energy non-conservation. The argument is the same as used to be used in the early days of the steady state theory. The work done by the large negative pressure during the expansion reappears as energy-density which can then remain constant despite the expansion.

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