HUTP-82/A060

MONOPOLES IN THE VERY EARLY UNIVERSE

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Talk presented at the Nuffield Workshop on the Very Early Universe
June 21 - July 9, 1982

To be published in *The Very Early Universe*, edited by S. W. Hawking, G. W. Gibbons and S. Siklos, Cambridge University Press, 1983.

*Research supported in part by the National Science Foundation under Grants PHY77-22864 and PHY82-15249, and by the Alfred P. Sloan Foundation.

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1 *INTRODUCTION*

In recent years, it has become increasingly popular in theoretical particle physics to speculate about the structure of matter at extremely short distances, distances of order 10^{-28} cm, or smaller. These speculations are frustrating, because to explore this very-short-distance physics experimentally would require experiments performed at correspondingly high energies, energies of order 10^{15} GeV, or higher. Such experiments will not be performed in any foreseen accelerator. Partly for this reason, some particle physicists have become interested in cosmology. For we believe that the universe was once extremely hot, so hot that collisions with energies of order 10^{15} GeV or above occurred copiously. We can therefore attempt to use the very early universe as our accelerator, and look today for relics of the very energetic past.

We have today a reasonably firm understanding of particle physics up to energies of order 100 GeV. This physics has been explored in accelerator experiments, and the experiments have tended to confirm our theoretical expectations. As a result, we can confidently extrapolate the standard big-bang cosmology (for a review see Peebles, 1971, or Weinberg, 1972) back to times of order 10^{-10} sec when the temperature of the universe was about 100 GeV. But to discuss the evolution of the universe at earlier times, we must be willing to speculate about particle physics at higher energies.

The currently fashionable grand unified theories are reputed to provide a complete description of particle physics up to energies of order 10^{19} GeV, where quantum gravitational effects, not yet encompassed by these theories, begin to play a significant role. They thus offer us an opportunity to analyze the evolution of the universe after the first 10^{-44} sec, when the temperature was below 10^{19} GeV. According to the most popular version of grand unification, particle physics at energies much greater

than 100 GeV closely resembles the physics we already know; only at energies of order 10^{15} GeV do new interactions with qualitatively different properties begin to assert themselves. If this "desert hypothesis" proves correct, it will be discouraging to experimental particle physicists. But it will also enhance the importance of cosmology to particle physicists, for the study of the very early universe will provide one of the few means at our disposal of exploring the new physics at energies of order 10^{15} GeV and beyond.

The universe was sufficiently hot to probe the new short-distance physics predicted by grand unified theories during only the first 10^{-35} sec. Fortunately, there are at least two relics from the first 10^{-35} sec that we have a good chance of observing today. One is the baryon number of the universe, which *has* been observed. The other is the magnetic monopole, which may have been observed. This talk is about the second relic.

Grand unified theories are briefly reviewed in Section 2, and the properties of magnetic monopoles are discussed in Section 3. The role of monopoles in cosmology is the subject of Section 4. The remainder of the talk concerns the prospects for observing monopoles. Theoretical limits on the flux of monopoles in cosmic rays are reviewed in Section 5, and the implications of a recently reported candidate monopole event are considered in Section 6. Remarks about experiments that may be performed in the future are contained in Section 7. Section 8 contains conclusions.

2 *GRAND UNIFICATION*

By a grand unified theory, I mean any particle physics model in which the standard low-energy gauge group $SU(3)_{color} \times [SU(2) \times U(1)]_{electroweak}$ is embedded in a simple gauge group G which is spontaneously broken at a large mass scale. (Actually most of what will be said applies also to the case of unification in a semi-simple gauge group.) The SU(5) model of Georgi and Glashow (1974) is the simplest of many possible models which satisfy this criterion; for a review see Langacker (1981). If one adopts the "desert hypothesis", that is, assumes that no unexpected new interactions or particles appear at intermediate energies, then the mass scale M_{GUT} at which unification occurs can be calculated; the prediction is $M_{GUT} \sim 10^{15}$ GeV (Georgi, Quinn and Weinberg, 1974). But it is important to bear in mind that the desert hypothesis may be wrong while the general idea of grand unification is still correct. Then the unification scale could be different.

If we do accept the desert hypothesis, then the relative strengths of the interactions observed at low energy can also be computed. In particular, the Weinberg angle can be predicted, and the prediction is in striking agreement with the measured value. (See Langacker, 1981.) This agreement is the best reason for believing the desert hypothesis.

Another very attractive feature of grand unification is that quantization of electric charge is naturally explained. Measured electric charges are always found to be integer multiples of the electron charge. In the standard SU(3) × SU(2) × U(1) model, this quantization is imposed by hand, but in grand unified theories, it is a necessity; the electric charge operator obeys nontrivial commutation relations with other operators in the theory, and just as the angular momentum algebra can require the eigenvalues of J_z to be integer multiples of $\frac{1}{2}\hbar$, so the commutation relations obeyed by the electric charge operator require its eigenvalues to be integer multiples of a fundamental unit.

Three general properties of grand unified models are particularly important in cosmology. First, the interactions mediated by particles with masses of order M_{GUT} typically fail to conserve baryon number. This property leads on the one hand to the prediction that the proton should decay, with a lifetime which can be estimated, if we accept the desert philosophy, to be 10^{29-33} yrs. Also, during the first 10^{-35} seconds, when the temperature was of order M_{GUT}, baryon number nonconserving processes occurred copiously. Therefore, any pre-existing initial baryon number was wiped out, and the abundance of baryons today can be calculated, in the context of a specific grand unified model, by considering the evolution of the baryon number density in the very early universe. The results of these calculations are quite model-dependent (for a detailed discussion, see Kolb and Wolfram, 1980, and Fry *et al.*, 1980), but it is not implausible that the observed relative abundance of baryons to photons, about 10^{-9}, was generated in this way.

Another important consequence of grand unification is that the universe is expected to have undergone a phase transition at a critical temperature T_c of order M_{GUT}. For $T > T_c$, the full grand unified gauge symmetry, which is spontaneously broken at low temperature, is restored. As we have heard from previous speakers (Guth, 1982; Linde, 1982b), this phase transition may have had a very significant effect on the evolution of the universe.

A third general consequence of grand unification turns out to be closely related to quantization of electric charge: The particle spectrum of a grand unified model necessarily contains magnetic monopoles, stable particles which carry magnetic charges. The necessity of magnetic monopoles in grand unified theories was demonstrated by 't Hooft (1974) and Polyakov (1974). But a general connection between electric charge quantization and magnetic monopoles was pointed out by Dirac (1931) many years earlier.

3 *MAGNETIC MONOPOLES*

Dirac envisaged a magnetic monopole as a semi-infinitely long, infinitesimally thin solenoid. One end of the solenoid, viewed in isolation, appears to be a magnetic charge. But it makes sense to identify this object as a magnetic monopole only if no conceivable experiment can detect the solenoid, in the limit in which it is infinitesimally thin.

We might imagine trying to detect the solenoid by doing an electron interference experiment; such an experiment gives a null result only if the phase picked up by the electron wave function, when the electron is transported along a closed path enclosing the solenoid, is trivial. Suppose a monopole with magnetic charge g sits at the origin, so that the magnetic field is

$$\vec{B} = g\,\frac{\hat{r}}{r^2}\ , \tag{1}$$

and that the solenoid lies on the negative z-axis. Then the vector potential can be written in polar coordinates as

$$\vec{A}\cdot d\vec{r} = g(1-\cos\theta)\,d\phi\ . \tag{2}$$

The electron interference experiment fails to detect the solenoid if

$$\text{phase} = \exp[-ie\oint\vec{A}\cdot d\vec{r}] = e^{-4\pi i e g} = 1\ , \tag{3}$$

where $-e$ is the electron charge. Hence, we require the magnetic charge g of the monopole to satisfy the quantization condition

$$g = \frac{n}{2e}\ , \tag{4}$$

where n is an integer. The minimal allowed charge $g_D = 1/2e$, is called the Dirac magnetic charge.

As Dirac (1931) observed, we can now turn this argument around, as follows: Suppose there exists a particle with electric charge Q and vanishing magnetic charge. Then it is consistent for a magnetic monopole with magnetic charge g_D to exist only if $\exp[4\pi i Q g_D] = 1$ or

$$\frac{Q}{e} = \frac{1}{2e\, g_D} m = m \;, \tag{5}$$

where m is an integer. Therefore, the existence of a magnetic monopole implies quantization of electric charge.

It may disturb you that, to derive the Dirac quantization, Eq. (4), I have used the electron charge $-e$. We would like to believe that quarks exist, and the electric charge of a down quark, for example, is $-\frac{1}{3}e$. Will not the same argument as before, applied to a down quark instead of an electron, lead to the conclusion that the minimal allowed magnetic charge is $3g_D$ instead of g_D?

No, not if quarks are confined. For if quarks are permanently confined in hadrons, it makes sense to speak of performing a quark interference experiment only over distances smaller than 10^{-13} cm, the size of a hadron. It is true that, when the down quark is transported around Dirac's solenoid, its wave function acquires the nontrivial phase

$$\exp[-i\frac{e}{3}\oint \vec{A}_{em}\cdot d\vec{r}] = e^{-i\,2\pi/3} \neq 1 \tag{6}$$

due to the coupling of the down quark to the electromagnetic vector potential, if the monopole carries the Dirac magnetic charge g_D. But we must recall that the down quark carries another degree of freedom, color. The solenoid is not detectable if the monopole also has a *color magnetic field*, such that the phase acquired by the down quark wavefunction due to the color vector potential compensates for the phase due to the electromagnetic vector potential, or

$$\exp[\, i\, e_c \oint \vec{A}_{color}\cdot d\vec{r}] = e^{i\,2\pi/3} \tag{7}$$

where e_c is the color gauge coupling.

The correct conclusion, then, is not that the minimal magnetic charge is $3g_D$, but rather that the monopole carrying magnetic charge g_D must also carry a color magnetic charge. The color magnetic field of the monopole becomes screened by nonperturbative strong interaction effects at

distances greater than 10^{-13} cm. (For more details, see Coleman, 1982.)

Dirac's argument shows that the existence of magnetic monopoles implies quantization of electric charge. The converse, in a certain sense, is also true. Any grand unified model, in which electric charge is quantized because the electromagnetic U(1) gauge group is embedded in a simple group which is spontaneously broken at the mass scale M_{GUT}, necessarily contains magnetic monopoles. This remarkable result was discovered by 't Hooft (1974) and Polyakov (1974).

The magnetic monopoles constructed by 't Hooft and Polyakov are topologically stable defects in the Higgs field which acts as an order parameter for the spontaneous breakdown of the grand unified gauge symmetry. The statement that these objects are topological means the following: A long distance away from the center of the monopole, the Higgs field asymptotically approaches in each direction a value which can be obtained by performing a gauge transformation on a standard vacuum value; however, it is impossible to perform a gauge transformation such that the Higgs field approaches the same constant value in all directions simultaneously. Under this circumstance, one says that the "sphere at infinity" is wrapped around the manifold of gauge-equivalent vacua in a topologically nontrivial way. As a consequence, the Higgs field configuration cannot fall apart, and is endowed with a conserved quantum number which turns out to be the magnetic charge. (For a much more detailed discussion, see Coleman, 1982.)

The properties of a monopole of the 't Hooft-Polyakov type, such as its size and mass, can be calculated in a given grand unified model. By the size r of the monopole, I mean the characteristic distance from the center of the monopole over which the Higgs field approaches its asymptotic value. That part of the monopole inside radius r is called the "core". The size r is determined by a compromise between the energy stored in the core of the monopole, which is of order $4\pi M_{GUT}^2 r$, and the magnetostatic field energy, which is of order $4\pi g^2/r$. The sum of these two terms is minimized for $r \sim M_{GUT}/g$. The magnetic charge of a grand unified monopole is typically the Dirac charge, so its properties may be summarized by

$$\text{Charge:}\quad g = g_D = 1/2e \;,$$

$$\text{Size:}\quad r \sim e^{-1} M_{GUT}^{-1} \sim M_X^{-1} \sim 10^{-28}\,\text{cm} \;,$$

$$\text{Mass:}\quad m \sim (4\pi/e^2) M_X \sim 10^{16}\,\text{GeV} \;, \tag{8}$$

where M_x is the typical mass of one of the heavy gauge bosons in the model. The numerical estimates of r and m in Eq. (8) are based on the standard estimate of M_x, derived from the desert hypothesis. The gauge coupling $e^2/4\pi$ is the running coupling constraint renormalized at the mass scale M_{GUT}, which is somewhat larger than $\alpha \sim 1/137$.

The grand unified monopole is unusually heavy for a stable elementary particle; the mass 10^{16} GeV $\sim 10^{-8}$g is comparable to the mass of a bacterium. We also see from Eq. (8) that the size r of the monopole is larger than its Compton wavelength by a factor of order $4\pi/e^2$. In this sense, the monopole is a nearly classical object; quantum mechanics plays an insignificant role in determining the structure of the monopole over distances of order r, in the limit in which e^2 is small.

Most of the mass of the monopole is concentrated in the tiny core of radius r, but the monopole also has structure on other, much larger, distance scales. In particular, as we have already remarked, the monopole is a hadron; it has a color magnetic field extending out to 10^{-13} cm. At distances larger than 10^{-13} cm, it interacts only electromagnetically.

While the prediction $m \sim 10^{16}$ GeV follows from the desert hypothesis, it is important to realize that the existence of magnetic monopoles is a very general consequence of grand unification, and that the monopole mass could be different. Monopoles occur in any model in which the electromagnetic U(1) is embedded in a spontaneously broken semisimple gauge group. The monopole mass is $m \sim 4\pi g M_{GUT}$, where g is the magnetic charge, and M_{GUT} is the symmetry breaking scale at which the U(1) gauge group first appears.

To put monopoles in the proper perspective, it is helpful to enumerate the stable particle spectrum of a typical grand unified theory. Nothing is stable in these theories unless there is a good reason. The photon is stable; it is presumably exactly massless. The lightest neutrino is stable, because it is the lightest fermion, and its decay is forbidden by angular momentum conservation. The electron is stable, because it is the lightest electrically charged particle, and electric charge is exactly conserved. And the lightest magnetic monopole is stable, because it is the lightest magnetically charged particle, and magnetic charge is exactly conserved. (The graviton is also stable, but I have not mentioned it, because the grand unified theories I have considered do not include gravity.)

4 *MONOPOLES AND COSMOLOGY*

A large class of particle physics models predict the existence of stable magnetic monopoles. But to say that monopoles exist is not necessarily to say that we have a reasonable chance of observing one. If the monopole mass is really as large as 10^{16} GeV, then there is no hope of producing monopoles in accelerator experiments in the foreseeable future. Let us consider, then, whether monopoles might have been produced in the very early universe (Zel'dovich and Khlopov, 1978; Preskill, 1979; for another review see Weinberg, 1982).

As was mentioned earlier, we expect that the complete gauge symmetry of a grand unified model is restored at temperatures $T > T_c \sim M_{GUT}$; the Higgs scalar field Φ has a vanishing expectation value for $T > T_c$ and a nonzero expectation value for $T < T_c$. But 't Hooft-Polyakov monopoles can exist only when the gauge symmetry is spontaneously broken; no monopoles are present while $T > T_c$. As the universe cools below T_c monopoles can be produced. Because monopoles, unlike the other superheavy particles in grand unified theories, are stable, the density of monopoles per comoving volume established in the phase transition at $T \sim T_c$ can be subsequently reduced only by annihilation of monopole-antimonopole pairs. As the universe expands, monopoles and antimonopoles have a more difficult time finding each other, and an appreciable density of monopoles per comoving volume might persist.

Thus, the problem of estimating the monopole abundance may be separated into two parts. We must estimate the initial density of monopoles established in the course of the phase transition, and we must determine to what extent the monopole density is subsequently reduced by pair annihilation. (I will assume that the densities of monopoles and antimonopoles are equal.)

Let us first consider the production of monopoles during the phase transition. The detailed mechanism by which monopoles are produced depends on the nature of the phase transition; in particular, on whether it is a second-order (or weakly first-order) transition, in which large fluctuations occur, or a strongly first-order transition, in which supercooling occurs. In either case, there is no reason to believe that the monopole density was ever in thermal equilibrium.

In the case of a second-order (or weakly first-order) phase transition, the Higgs field Φ, which acts as an order parameter for the transition, undergoes large random fluctuations for $T \sim T_c$. As the universe expands and cools, the Higgs field is rapidly quenched, and a large density of topological defects becomes frozen in; these defects are the monopoles and antimonopoles. The quenching process can be described in the following way (Kibble, 1976): At the time that monopoles are being produced, the Higgs field is uncorrelated over distances larger than some characteristic correlation length ξ. We may thus regard the Higgs field as having a domain structure, with ξ the characteristic size of a domain. At the intersection point of several domains, each with a randomly oriented Higgs field, there is some probability p that the Higgs field configuration is topologically nontrivial; if so, a monopole or antimonopole must form at the intersection point. The probability p depends on the detailed structure of the monopole, but it is not very much less than one. According to the above picture, the density of monopoles initially established in the phase transition is

$$(n)_{\text{initial}} \sim p\,\xi^{-3} \quad . \tag{9}$$

This argument sounds suspicious, because it relies on the notion of a Higgs field domain structure, although it is always possible to make a uniform Higgs field look wiggly by performing a gauge transformation. However, there is no fundamental difficulty. We may always fix the gauge in some appropriate way so that the idea of a Higgs field domain makes sense, and we have reached a conclusion about the density of topological defects, which is a gauge-invariant quantity.

It is not clear how best to go about calculating ξ, but we can easily obtain an upper bound on ξ from a simple causality argument (Einhorn *et al.*, 1980; Guth and Tye, 1980). The Higgs field must be uncorrelated over distances exceeding the horizon length d_H, the largest distance any signal could have traveled since the initial singularity; thus $\xi < d_H$. In terms of the temperature T, d_H is given by

$$\xi < d_H \sim \frac{Cm_p}{T^2} \quad . \tag{10}$$

Here $m_p \sim 10^{19}$ GeV is the Planck mass, and $C = (0.60)N^{-1/2}$, where N is the effective number of massless spin degrees of freedom in thermal equilibrium at temperature T; in a minimal grand unified theory, $C \sim 1/20$. Combining (9) and (10), we conclude that the initial value of the dimensionless quantity n/T^3 is bounded by

$$(n/T^3)_{\text{initial}} \gtrsim p(T_c/Cm_p)^3 \quad . \tag{11}$$

In a typical grand unified theory with $T_c \sim 10^{15}$ GeV, $Cm_p \sim 10^{18}$ GeV, and $p \sim 1/10$, we obtain $(n/T^3)_{\text{initial}} \gtrsim 10^{-10}$.

In the case of a strongly first-order phase transition, supercooling occurs. The phase with unbroken grand unified gauge symmetry becomes unstable when $T < T_c$, but nonetheless persists for a while, until bubbles of the stable broken-symmetry phase eventually begin to nucleate. These bubbles expand, collide, and coalesce, filling the universe with the stable phase (Coleman, 1977). Inside each bubble, the Higgs field is quite homogeneous, so that each bubble contains a negligible number of monopoles. But when the expanding bubbles collide, monopoles can be produced.

Although it is not easy to calculate in detail the initial density of monopoles produced by bubble collisions, we can obtain a lower bound on the monopole density by invoking an argument similar to the one applied above to the case of a second-order transition. Now each bubble can be regarded as a Higgs field domain, and the density of monopoles produced by the collisions must exceed the probability factor p times the density of bubbles at the time they collide. Since bubbles cannot expand faster than the speed of light, each bubble must be smaller than the horizon size d_H, and the density of bubbles is greater than d_H^{-3}. Therefore, we conclude again that $n > p\,d_H^{-3}$, and the bound (11) still holds, except that T_c is replaced by a nucleation temperature T_n, at which nucleation becomes probable.

Let us now consider how the initial abundance of monopoles established in the phase transition subsequently evolves. Once the phase transition is complete, the rate of monopole production is negligible compared to the expansion rate of the universe; we may therefore ignore it. We will also neglect correlations between the positions of monopoles and antimonopoles; this approximation is reasonable when the monopole density is sufficiently small. The monopole density n is then governed by a rate equation of the form

$$\begin{aligned} dn/dt &= -(\text{Annihilation Term}) - (\text{Expansion Term}) \\ &= -D(T)n^2 - 3(\dot{R}/R)n \ , \end{aligned} \tag{12}$$

if the monopole and antimonopole densities are assumed to be equal. The factor D(T) is determined by the dominant annihilation process at a given temperature. At high temperature, there is a dense plasma of light electrically charged particles. This plasma aids the annihilation process, because it dissipates the energy of a monopole drifting toward a nearby antimonopole, allowing capture to occur. Once a bound monopole-antimonopole pair forms, it quickly cascades down, emitting many photons and gluons, and finally annihilates into a burst of Higgs particles and X-bosons. To estimate the annihilation rate, then, we must estimate the capture rate.

The drift velocity of a monopole in the plasma is independent of the monopole mass m. Since the coupling of a monopole to a charged particle is $eg = O(1)$, it is easy to guess that $D(T) \gtrsim g^2T/n_{ch}$, where n_{ch} is the density of light electrically charged particles, roughly given by N_cT^3, if N_c is the number of species of light charged particles in thermal equilibrium. The monopole density n will tend to adjust so that the two terms on the right-hand side of Eq. (12) are of the same order of magnitude. Since $\dot{R}/R \sim T^2/Cm_p$, we obtain

$$\frac{n}{T^3} \sim \left(\frac{N_c}{g^2}\right)\left(\frac{T}{Cm_p}\right) . \tag{13}$$

The diffusive capture process described above operates effectively only if the mean free path λ of a monopole in the plasma is shorter than the characteristic distance $\lambda_c \sim g^2/T$ at which capture can occur. But $\lambda \sim (1/N_cT)(m/T)^{1/2}$ becomes comparable to λ_c when $T \sim m/g^4N_c^2$; at lower temperatures this capture process is cut off. When diffusive capture ends, the monopole density is given by (Preskill, 1979)

$$\frac{n}{T^3} \sim \frac{1}{N_c g^6}\,\frac{m}{Cm_p} . \tag{14}$$

If the initial value of n/T^3 is smaller than the right-hand side of (14), then the annihilation rate never competes with the expansion rate, and n/T^3 is unchanged.

At lower temperatures, monopoles and antimonopoles must shake off photons or gluons in order to capture each other. This process is too inefficient to keep pace with the Hubble expansion (Preskill, 1979; Dicus *et al.*, 1982), and n/T^3 remains frozen at the value given in Eq. (14).

Plugging in the standard estimates, $m \sim 10^{16}$ GeV, $Cm_p \sim 10^{18}$ GeV, $N_c g^6 \sim 10^7$, Eq. (14) becomes $n/T^3 \sim 10^{-9}$. Therefore, if the smallest possible initial monopole density per comoving volume consistent with the bound (11), $n/T^3 \sim 10^{-10}$, is established in the phase transition, it is not further reduced by annihilation at all. The only way to reduce n/T further is through nonadiabatic effects which increase the entropy density,

but such effects cannot dilute the monopole abundance by many orders of magnitude without at the same time diluting the baryon excess. Neglecting generation of entropy, we conclude that the density of magnetic monopoles today is $n \sim 10^{-10}\,T^3$, which is comparable to the density of baryons. This conclusion is clearly absurd, if the mass of a monopole exceeds the mass of a baryon by a factor of order 10^{16}.

We have uncovered the "monopole problem", an apparently serious conflict between grand unified theories and standard big-bang cosmology. Various attempts have been made to resolve this conflict. These attempts tend to fall into two categories. Some authors have suggested mechanisms which enhance the monopole-antimonopole annihilation rate; others have suggested ways of suppressing the initial production of monopoles in the phase transition.

If the monopole density were really $n \sim 10^{-10}T^3$, the universe would become matter dominated by monopoles at a relatively early time, and the monopoles would be expected to condense into clumps in which the annihilation rate would be enhanced. A detailed analysis of this scenario, however, indicates that this enhancement does not suffice to reduce the monopole abundance to an acceptable level (Goldman *et al.*, 1981; Fry, 1981; Dicus *et al.*, 1982).

Mechanisms have been advanced in which monopoles and antimonopoles form bound pairs connected by flux tubes. Were this to occur, pair annihilation would swiftly reduce the monopole abundance to an acceptable value. One proposal (Linde, 1980) is that the color magnetic field of the monopole is confined to a flux tube at high temperature. Another (Lazarides and Shafi, 1980) is that, at least in some models, monopoles and antimonopoles become connected by Z^0 flux tubes after the weak interaction symmetries get spontaneously broken at $T \sim 300$ GeV. In both cases, however, the proposed flux tubes are not topologically stable, and their existence has not been demonstrated.

Langacker and Pi (1980)(see also Bais and Langacker, 1982) *have* succeeded in constructing a scenario in which monopole-antimonopole pairs become confined by flux tubes. Their proposal is that, over some temperature range, the U(1) gauge group of electromagnetism is spontaneously broken, which causes the U(1) magnetic flux to collapse to a tube. Specifically, they constructed a model which undergoes, as the temperature decreases, the sequence of phase transitions

$$SU(5) \rightarrow SU(3) \times SU(2) \times U(1) \rightarrow SU(3) \rightarrow SU(3) \times U(1) . \tag{15}$$

While the universe is in the SU(3) phase, any previously produced monopoles are expected to annihilate, and when the transition to the SU(3) × U(1) phase finally occurs, the temperature is so low that an acceptably small monopole abundance is generated. Unfortunately, to achieve the symmetry breaking pattern in Eq. (15), Langacker and Pi must impose on their model a complicated and contrived Higgs structure. Nonetheless, theirs is a viable proposal for reducing the monopole abundance.

Among suggested means of reducing the initial monopole abundance established in the phase transition, one proposal (Bais and Rudaz, 1980) is that the large fluctuations in the Higgs field at temperatures near T_c in a second-order phase transition allow the monopole density to relax to a very small value. But it has not been explained how this mechanism can generate the acausal correlations needed to defeat the bound (11).

Our discussion of monopole production by bubble collisions in the case of a strongly first-order phase transition left open the possibility that the initial monopole density is suppressed if bubble nucleation is delayed long enough. But a detailed analysis (Guth and Weinberg, 1982) in the context of the "old" inflationary universe (Guth, 1981) indicates that, if nucleation is sufficiently delayed for the monopole abundance to be significantly suppressed, then the phase transition never finishes, and a conventional cosmological scenario cannot be recovered.

Another possibility is that, contrary to the desert hypothesis, the electromagnetic U(1) is embedded in a semisimple gauge group which is spontaneously broken at the mass scale $M_U \ll 10^{15}$ GeV. For $M_U \leqslant 10^9$GeV, the bound (11) gives an acceptably small monopole density. (Observational limits on the monopole abundance are discussed in Section 5; for light monopoles, $m \leqslant 10^{11}$GeV, $n/T^3 \leqslant 10^{-29}$ is required.) But this suggestion should be regarded with caution, because it requires that we take (11) seriously as an *equality*, not just a bound. That is, we must believe that the relevant correlation length which determines the initial monopole abundance is really the largest possible length d_H, and not a much shorter length. I think that this assumption has a far better chance of being justified in the case of a strongly first-order phase transition than in the case of a second-order (or weakly first-order) phase transition. (Even for light monopoles, annihilation cannot reduce an initially large monopole density to an acceptable level.)

Naturally, there is no monopole problem if there are no monopoles. The monopole problem does not arise if the electromagnetic U(1) is

not embedded in a spontaneously broken semisimple gauge group; that is, if the basic premise of grand unification is simply wrong.

Surely the most attractive proposal for suppressing the initial abundance of monopoles established in the grand unified phase transition is the new inflationary universe scenario (Linde, 1982a; Albrecht and Steinhardt, 1982). As we have heard from some of the previous speakers (Guth, 1982; Linde, 1982b; Steinhardt, 1982), one arranges in this scenario, at the cost of some fine tuning of parameters, that the universe undergoes many e-foldings of inflation *after* the appearance of bubbles or fluctuation regions in which the Higgs field is nonzero. Some monopoles are produced when bubbles or fluctuation regions first form, but they are subsequently "inflated away"; in the course of the exponential inflation, the monopole density is reduced to a negligible value. Eventually, the cosmological constant which drove the exponential inflation becomes rapidly thermalized, and the universe "reheats". During this thermalization process, some monopoles may be produced. Let us try to estimate how many (Turner, 1982; Lazarides *et al.*, 1982).

For the purpose of an order of magnitude estimate, we suppose that all light degrees of freedom instantaneously assume thermal distributions characterized by a reheating temperature $T_R \ll m$, and ask how the monopole density, chosen to vanish at temperature T_R, subsequently evolves, in a standard radiation-dominated cosmology. Neglecting pair annihilation, the monopole density is determined by the rate equation

$$\frac{dn}{dt} = (\text{Production Term}) - (\text{Expansion Term})$$

$$= D(T)\, n_{eq}^2(T) - 3(\dot{R}/R)n\,, \tag{16}$$

where D(T) is the same function as appears in Eq. (12), and $n_{eq} \sim (mT)^{3/2} e^{-m/T}$ is the equilibrium density of monopoles at temperature T. This form of the monopole production term in the rate equation is obtained by a standard detailed-balance argument; if the monopole density did assume the equilibrium value, then the monopole production and annihilation rates would have to be equal. In response to the objection that the cross section for production of monopole-antimonopole pairs in hard binary collisions is suppressed by a factor of the form e^{-c/e^2}, because monopoles are large compared to their Compton wavelength (Witten, 1979a; Drukier and Nussinov, 1982), we note that the monopole production rate is dominated by many-particle processes, not binary collisions.

Substituting $\dot{R}/R \sim T^2/m_p$ and $D(T) \sim g^2/T^2$, as in our discussion of monopole-antimonopole annihilation, Eq. (16) may be rewritten

$$\frac{d}{dT^{-1}}\left(\frac{n}{T^3}\right) \sim g^2 m_p \left(\frac{m}{T}\right)^3 e^{-2m/T}, \tag{17}$$

which, when integrated from $T = T_R$ to $T = 0$, yields

$$\frac{n}{T^3} \sim g^2 \frac{m_p}{m}\left(\frac{m}{T_R}\right)^3 e^{-2m/T_R}. \tag{18}$$

Since the ratio m/T_R appears in the exponent, it should be estimated carefully; let us consider an explicit example.

In the new inflationary universe scenario, the reheating temperature T_R can be estimated fairly precisely; the effective potential is required to satisfy the Coleman-Weinberg (1973) condition, and the vacuum energy in the symmetric phase can therefore be expressed in terms of gauge boson masses. Assuming that this vacuum energy is shared among all thermalized radiation species after reheating, the reheating temperature can be computed. In the "minimal" SU(5) model one finds $T_R \sim M_X/6.2$. The monopole mass can also be accurately estimated when the Coleman-Weinberg condition holds; in the minimal SU(5) model it is $m \sim \alpha_{GUT}^{-1} M_X$, where $\alpha_{GUT} \sim (42)^{-1}$ is the gauge coupling, renormalized at the unification scale. For the minimal SU(5) model, then, Eq. (18) becomes

$$\frac{n}{T^3} \sim (6\,\alpha_{GUT}^{-1})^3 \left(\frac{m_p}{M_X}\right) e^{-(12.4)\alpha_{GUT}^{-1}} \sim 10^{-20} \ . \tag{19}$$

This is discouraging; if the monopole density is really as small as indicated in Eq. (19), we will never see a monopole.

I have presented two theoretical estimates of the monopole abundance. One, Eq. (11), is unacceptably large. The other, Eq. (19) is depressingly small. It is hardly necessary to add that estimates anywhere in between can easily be obtained. For example, I can construct grand unified models in which the gauge coupling at unification is larger than in the minimal SU(5) model, so that m/T_R is smaller, and the abundance given by Eq. (18) is larger. There is no precise theoretical expectation of what the cosmological monopole abundance should be.

The qualitative prediction is nonetheless significant. Grand unified theories require the existence of magnetic monopoles. These monopoles could have been produced in the very early universe. In the new inflationary universe scenario it is possible for the monopole abundance to be both small enough to be acceptable and large enough to be observable. Clearly, we should look for them.

5 *LIMITS ON THE MONOPOLE FLUX*

People have been looking for magnetic monopoles for a long time. But one quickly recognizes that the traditional monopole search experiments do not place significant constraints on superheavy monopoles with mass m of order 10^{16} GeV. These traditional searches have relied on the strong ionization power of relativistic monopoles (Fleischer *et al.*, 1969; Price *et al.*, 1978) or have sought monopoles trapped in the earth's crust (Kolm *et al.*, 1971; Alvarez *et al.*, 1971). But a superheavy monopole would be expected to be slowly moving and very penetrating; it need not ionize heavily or stop in the earth (Preskill, 1979; Lazarides *et al.*, 1981).

How slowly moving? The monopole can be accelerated by either gravitational fields or magnetic fields; which effect is more important depends on the mass of the monopole. From gravitational fields alone, the monopole would acquire a typical galactic infall velocity, of order 10^{-3}c, regardless of its mass. To determine the effect of the magnetic field in our galaxy, recall that the field has a strength B of order 3×10^{-6} gauss and a coherence length L of order 10^{21} cm (see Parker, 1979). A monopole with the Dirac charge g_D crossing one coherence length is accelerated to

$$v = \left(\frac{2g_D BL}{m}\right)^{1/2} \sim 3\times10^{-3}c\left(\frac{B}{3\times10^{-6}q}\right)^{1/2}\left(\frac{L}{10^{21}\,\mathrm{cm}}\right)^{1/2}\left(\frac{10^{16}\,\mathrm{GeV}}{m}\right)^{1/2} . \tag{20}$$

This magnetic acceleration is therefore more important than the gravitational acceleration for $m \leqslant 10^{17}$ GeV. The monopole does not attain a relativistic velocity for $m > 10^{11}$ GeV.

How penetrating? The stopping power of slowly moving magnetic monopoles remains a rather controversial subject, about which a little more will be said later. But the energy loss in rock of a monopole with $v/c \leqslant 10^{-2}$ is surely not much larger than (Ahlen and Kinoshita, 1982)

$$\frac{dE}{dx} \sim 100\left(\frac{v}{c}\right)\mathrm{GeV/cm} \ . \tag{21}$$

Thus the range in rock of a monopole with $m \sim 10^{16}$ GeV is larger than 10^{11} cm;

the monopole passes through the earth without slowing down.

Although superheavy monopoles are not easily stopped or detected, there are nonetheless quite severe limits on the flux of magnetic monopoles in cosmic rays. (For a review, see Fry, 1982.) One limit on the number density of monopoles can be obtained because monopoles are very heavy, and has nothing to do with their magnetic charge. Demanding that the mass density due to monopoles not exceed the observational limit $\rho \leqslant 10^{-29}\,\mathrm{g\,cm^{-3}}$, we obtain the bound

$$n \leqslant 10^{-21}\,\mathrm{cm}^{-3}\left(\frac{10^{16}\,\mathrm{GeV}}{m}\right) \qquad (22)$$

on the monopole density n. Using the estimate (20) for the monopole velocity, which is valid for $m \leqslant 10^{17}\,\mathrm{GeV}$, we obtain a limit on the monopole flux,

$$nv \leqslant 10^{-2}\,\mathrm{m}^{-2}\mathrm{yr}^{-1}\left(\frac{10^{16}\,\mathrm{GeV}}{m}\right)^{3/2} \qquad (m \leqslant 10^{17}\,\mathrm{GeV}). \qquad (23)$$

If the monopole mass exceeds $10^{17}\,\mathrm{GeV}$, it is conceivable that monopoles are confined to galactic halos. Thus, the local density could be considerably higher than the bound (22). Assuming that the mass of the halo is less than 10^{12} solar masses, and that the typical monopole velocity is $10^{-3}c$, we obtain the flux limit

$$nv \leqslant 10^{2}\,\mathrm{m}^{-2}\mathrm{yr}^{-1}\left(\frac{10^{17}\,\mathrm{GeV}}{m}\right) \qquad (m \geqslant 10^{17}\,\mathrm{GeV}). \qquad (24)$$

A somewhat more restrictive flux limit is obtained by a slightly less direct argument, due to Parker (1970). (See also Turner *et al.*, 1982.) The galactic magnetic field accelerates monopoles. Thus, the energy density $U = B^2/8\pi$ stored in the field is dissipated at the rate $dU/dt \sim \langle g n\vec{v}\cdot\vec{B}\rangle$. By demanding that the field energy is not substantially depleted in a time τ, of order 10^8years, required to regenerate the field, we obtain the limit

$$nv \leqslant \frac{B}{8\pi g \tau} \sim 2\times 10^{-4}\,\mathrm{m}^{-2}\mathrm{yr}^{-1}\left(\frac{B}{3\times 10^{-6}\,\mathrm{gauss}}\right)\left(\frac{10^8\,\mathrm{yr}}{\tau}\right). \qquad (25)$$

A nice feature of this flux limit is that it appears to be independent of the mass m of the monopole.

However, it is implicitly assumed in the derivation of (25) that gravitational effects on the trajectory of the monopole are neglibible,

and we have already argued that this is not so for $m \geqslant 10^{17}\,\mathrm{GeV}$. If a monopole enters a coherent domain of the galactic magnetic field with incident energy $\frac{1}{2}mv^2 > gBL$, then the energy it extracts from the domain is a second-order effect, due to the deflection of the monopole trajectory as it crosses the domain; on the average it is (Turner *et al.*, 1982)

$$\Delta E \sim (gBL)^2/\tfrac{1}{2}mv^2 \,. \qquad (26)$$

Therefore, the rate of dissipation of magnetic field energy scales like 1/m for $m \geqslant 10^{17}\,\mathrm{GeV}$, and our flux limit becomes

$$nv \leqslant 2\times 10^{-4}\,\mathrm{m}^{-2}\mathrm{yr}^{-1}\left(\frac{m}{10^{17}\,\mathrm{GeV}}\right)\left(\frac{B}{3\times 10^{-6}\,\mathrm{gauss}}\right)\left(\frac{10^8\,\mathrm{yr}}{\tau}\right) \qquad (m \geqslant 10^{17}\,\mathrm{GeV}). \qquad (27)$$

This crosses the constraint (24) for $m \sim 10^{20}\,\mathrm{GeV}$; therefore, combining (24) and (27), we can obtain the mass-independent flux limit

$$nv \leqslant 10^{-1}\mathrm{m}^{-2}\mathrm{yr}^{-1} \,. \qquad (28)$$

It should be admitted, though, that the above arguments are rather naive, particularly for the case of monopoles which are heavy enough to remain confined to galaxies. We have treated monopoles as test particles riding the galactic magnetic field. If, instead, magnetic charge density fluctuations play a significant part in establishing the field, it is conceivable that the Parker limit (27) can be exceeded (Turner *et al.*, 1982; Salpeter *et al.*, 1982).

In view of (27) I had been saying for several years that anyone who wished to do a useful experiment to search for superheavy magnetic monopoles should think about how to build a very big detector. It appeared to be necessary to cover a football field in order to have a reasonable chance of seeing one monopole in a year. I was surprised when I heard that a candidate monopole event had been observed in a detector smaller than the palm of my hand.

6 *THE CABRERA EXPERIMENT*

The experiment was performed by Blas Cabrera (1982a), at Stanford. Briefly, the apparatus consists of a coil of superconducting wire with radius r = 2.5 cm and N = 4 turns. (For a more detailed description see Cabrera, 1982b.) The current in the wire is monitored by a SQUID. What happens if a magnetic monopole passes through the coil?

The relevant integrated Maxwell equation, suitably modified for the existence of a magnetic monopole current, is

$$\oint_\Gamma \vec{E}\cdot d\vec{r} = -\frac{1}{c}\frac{d\Phi}{dt} - \frac{4\pi}{c}\frac{dQ_m}{dt} , \tag{29}$$

where Φ is the magnetic flux through a surface S_Γ bounded by the closed path Γ, and dQ_m/dt is the magnetic monopole current flowing through S_Γ. Applying Eq. (29) to a path entirely contained in the superconducting wire, where $\vec{E} = 0$, and integrating over time, we find that the change $\Delta\Phi$ in the magnetic flux linking the coil and the total magnetic charge ΔQ_m which passes through the coil are related by

$$\Delta\Phi = -4\pi N \Delta Q_m . \tag{30}$$

In particular, if a magnetic monopole with magnetic charge g passes through a coil with $N = 4$ turns, the change in the magnetic flux will be

$$\Delta\Phi = -8\Phi_0\left(\frac{g}{g_D}\right) , \tag{31}$$

where $g_D = 1/2e$ is the Dirac magnetic charge, and $\Phi_0 = 4\pi g_D/2$ is the flux quantum of the superconductor; the factor of two arises because the electric charge of a Cooper pair is 2e.

Hence, a monopole passing through Cabrera's coil would cause a sudden change in the flux linking the coil, and a corresponding shift in the DC current level in the wire, which would be detected by the SQUID. One such event has been seen (on 14 February 1982, at 1:53 p.m., P.S.T.) with $|\Delta\Phi| \sim 8\Phi_0$.

An important advantage of Cabrera's detector is that it is sensitive to monopoles of arbitrarily low velocity. It is therefore conceivable that his detector could register a genuine monopole event while a much larger detector with a velocity threshold would see no evidence of monopoles. However, a single event cannot be taken very seriously; confirmation is sorely needed. I will nonetheless suppose in the following discussion that Cabrera has really discovered a monopole, and will consider the implications of this discovery.

If Cabrera's event was caused by a monopole, then he has

measured the magnetic charge of the monopole; it is consistent with the Dirac charge g_D. Ironically, this result appears to be in conflict with the result of another celebrated experiment performed at Stanford, the reported discovery by Fairbank and collaborators (LaRue *et al.*, 1977; 1979; 1981) of fractional charge on matter. Dirac's very general reasoning, reproduced in Section 3, indicates that the existence of monopoles with magnetic charge $g_D = 1/2e$ is inconsistent with the existence of *isolated* electrically charged particles carrying electric charge e/3.

Actually, there *are* theoretically acceptable ways of reconciling these two experiments. One amusing possibility is that the objects which carry fractional electric charge are actually "dyons" which also carry magnetic charge. For two dyons with electric and magnetic charges (Q_1, g_1) and (Q_2, g_2), the Dirac consistency condition becomes generalized to (Schwinger, 1966; Zwanziger, 1968)

$$Q_1 g_2 - Q_2 g_1 = n/2 , \tag{32}$$

where n is an integer, and Eq. (32) is satisfied if the electric charge q of an object with magnetic charge g is given by

$$Q/e = m + e g \theta/\pi , \tag{33}$$

where m is an integer; θ is an arbitrary parameter which may take any value from $-\pi$ to π (Witten, 1979b). The minimal electric charge carried by a dyon with the Dirac magnetic charge is $Q = e\theta/2\pi$. It is conceivable that Fairbank and Cabrera have discovered the same object; that Fairbank has measured its electric charge, and Cabrera has measured its magnetic charge, although I know of no reason why $\theta/2\pi$ should be close to 1/3. In any event, this theoretical possibility appears to be experimentally excluded. Cabrera (1982b) has measured the magnetic charges of two niobium spheres on which fractional electric charge has been observed; the measured magnetic charges were consistent with zero.

Another possible way to reconcile the two measurements is to postulate the existence of a new long-range force which couples to Cabrera's magnetic monopoles and Fairbank's fractional electric charges, but not to ordinary matter. I will not pursue this possibility here; for a discussion see Preskill, 1982; Strominger, 1982; Barr *et al.*, 1982; Pantalone, 1982.

A second implication of Cabrera's event, if we assume that it was really caused by a monopole, concerns the monopole flux. Clearly, it is an exaggeration to say that a single event constitutes a measurement of the flux, but it is improbable that an event would be observed in a detector with an area of 20 cm^2 in less than a year of running if the flux is much less than

$$nv \sim 5 \times 10^2 \, m^{-2} \, yr^{-1} \ . \qquad (34)$$

Disturbingly, this flux is more than six orders of magnitude above the Parker limit (25), which applies for $m \lesssim 10^{17}$ GeV, and nearly four orders of magnitude above the mass-independent limit (28). Perhaps it is possible, as suggested earlier, for the limit (28) to be exceeded by several orders of magnitude, if the galactic magnetic field is produced by magnetic charge density fluctuations (Salpeter *et al.*, 1982), but if we take (28) seriously (as I am inclined to), then we are forced to conclude that the monopole flux at Stanford is considerably larger than the ambient flux in our galaxy. Why should Stanford occupy such a privileged position?

A possible answer is that Stanford is close to a star, our sun (Dimopoulos *et al.*, 1982a). A flux incident on the solar system which nearly saturates the Parker limit might be able to maintain a monopole "cloud" surrounding the sun with a significantly enhanced monopole density, if monopoles passing through the sun (or Jupiter) are able to lose enough energy to become captured in solar orbit. It is unclear whether this mechanism can provide the necessary flux enhancement of at least four orders of magnitude, but if it can, one is led to the interesting prediction that the monopole flux incident on the earth is anisotropic, and that the typical monopole velocity is of order 10^{-4}c, the velocity of the earth in its orbit about the sun. The angular distribution and velocity distribution of monopoles should resemble those of meteorites, which are also projectiles in solar orbit.

7 *FUTURE EXPERIMENTS*

Many experiments currently running or planned have been specifically designed to search for superheavy magnetic monopoles. I will not attempt to review them all. For detailed accounts of many of these experiments, see Carrigan and Trower, 1982.

Several experiments have recently reported limits on the cosmic ray flux of slowly moving, weakly ionizing particles. (For a review see

Giacomelli, 1982.) An understanding of the ionization loss of slowly moving monopoles is necessary in order to extract from these results a limit on the monopole flux. On the basis of the best available estimates of the ionization loss (Ahlen and Kinoshita, 1982), it is conservative to conclude that the flux of monopoles with velocity $v \geqslant 10^{-3}$c satisfies

$$nv \leqslant 1 \, m^{-2} \, yr^{-1} \ . \qquad (35)$$

Therefore, if Cabrera's event was caused by a monopole, it was probably a very slow monopole with $v < 10^{-3}$c. This observation makes the solar cloud scenario seem more attractive.

Is it possible to build a non-induction detector which will reliably respond to a monopole with $v \sim 10^{-4}$c? Unfortunately, the stopping power of a monopole with $v \leqslant 10^{-3}$c is quite uncertain. One is inclined to say that the response of an atom or molecule to a very slowly moving monopole passing nearby is similar to its response to a magnetic field which adiabatically turns on and off; therefore, it is unlikely to become excited. But this conclusion is not necessarily correct, because the very strong magnetic field of the monopole greatly distorts the energy levels of the atom or molecule; if the ground state and an excited state closely approach each other, the adiabatic approximation may fail badly. To decide whether this occurs, detailed knowledge of the level structure in the inhomogeneous magnetic field of the monopole is needed. In fact, recent calculations (Drell *et al.*, 1982) have shown that the energy loss in atomic hydrogen and in helium of a monopole with velocity between 10^{-4}c and 10^{-3}c is much higher than previously suspected. This energy loss is almost exclusively due to atomic excitation followed by photon emission, with negligible ionization loss. It is not yet clear to what extent this result will generalize to other materials.

The top priority of present and future monopole search experiments is to obtain more events, either in induction devices like Cabrera's or in non-induction detectors. But assuming that enough events are accumulated to confirm the discovery of the monopole to everyone's satisfaction, what more can be learned by doing more intricate experiments? To test the predictions of the solar cloud hypothesis, measurements of the angular distribution and velocity distribution of monopoles incident on the earth are needed. Such measurements could be performed with an array of superconducting coils, each similar to Cabrera's device. To measure velocities up to $10^{-3}c$ over distances less than one meter, it is necessary to resolve time delays of less than a microsecond.

It is obviously very important to measure the mass of the monopole; to do so, the trajectory of the monopole must be measurably deflected. A monopole with the Dirac magnetic charge, mass m, and velocity v, if exposed to a magnetic field B perpendicular to its path over a path length L, is deflected by

$$\theta \sim 2\times10^{-6}\,\text{radians}\left(\frac{10^{16}\,\text{GeV}}{m}\right)\left(\frac{10^{-4}c}{v}\right)^2\left(\frac{BL}{100\,\text{kG}-\text{m}}\right) . \qquad (36)$$

To place interesting limits on the monopole mass, reasonably good angular resolution is required. One way of achieving improved angular resolution is being pursued by Cabrera (1982b). His group is developing a new detector, in which a thin cyllindrical sheet of superconducting material is used to record the track of a monopole. A monopole passing twice through the sheet leaves in its wake two vortices, each carrying two flux quanta; the vortices remain pinned, and determine the trajectory. The angular resolution is intrinsically limited only by the size of a vortex, about 10^{-6}m, divided by the distance between the vortices. Two such detectors, with a magnet in between, could serve as a monopole mass spectrometer, provided that the velocity is also measured.

Studying the monopoles that fall out of the sky is inconvenient. It would be much easier to measure the mass of a stationary monopole, or one moving at a velocity much less than $10^{-4}c$. Although the abundance of monopoles in the earth's crust is probably extremely small, the advantages of finding a monopole stuck in a rock are so great that a careful search is appropriate. One such search, which will process 10^6 tons of iron ore per year, is planned (Cline, 1982). To hold on to a monopole once you find it is problematic, but one should at least have the opportunity to make some measurements as the monopole begins its descent toward the center of the earth.

With a stationary or very slowly moving monopole, another extremely interesting measurement could be made - a measurement of the electric charge of the monopole. We have noted that the electric charge of a monopole with the Dirac magnetic charge is $Q = e\theta/2\pi$, where the angle θ is a parameter which characterizes the CP-nonconservation of electrodynamics (Witten, 1979b). The only way to determine θ is by measuring the electric charge of a monopole.

I have saved for last some comments about the most intriguing

recent development in monopole theory, which concerns the catalysis by monopoles of baryon number nonconserving processes. There is no doubt that the monopoles of a typical grand unified theory are capable of catalyzing baryon number nonconserving processes, such as nucleon decay (Dokos and Tomaras, 1980; Blaer *et al.*, 1981; Wilczek, 1982). The remarkable new suggestion of Rubakov (1981; 1982) and Callan (1982) is that the cross sections for such processes are independent of the size of the monopole core, and hence much larger than previously believed. In fact, Rubakov and Callan claim that monopoles catalyze nucleon decay at a rate typical of the strong interactions. In my opinion, this claim has not yet been convincingly demonstrated, but we may nevertheless consider its implications.

The most interesting, and disturbing, implication concerns the effects of monopoles in neutron stars (Kolb *et al.*, 1982; Dimopoulos *et al.*, 1982b). Surrounded by matter at nuclear density, monopoles behaving as suggested by Rubakov and Callan catalyze nucleon decay at a furious rate. A modest number of monopoles in a neutron star would raise the luminosity of the star to the point where it emits a substantial flux of ultraviolet or x-ray photons. Since neutron stars capture any monopoles incident on them, one obtains from observational limits on the diffuse ultraviolet and x-ray spectrum a limit on the product of the cross section σ for monopole-catalyzed nucleon decay and the interstellar monopole flux nv, namely

$$\left(\frac{\sigma}{10^{-27}\,\text{cm}^2}\right) nv \leqslant 10^{-12}\ \text{m}^{-2}\,\text{yr}^{-1} . \qquad (37)$$

If σ is really a strong-interaction cross section, we infer that the interstellar monopole flux must be smaller than the Parker limit, Eq. (25), by at least eight orders of magnitude. Apparently, if the cross section for monopole-catalyzed baryon number nonconservation is as large as Rubakov and Callan claim, monopoles are so rare that there is little hope of observing them directly, even if the local flux is substantially enhanced. The best way to find evidence for the existence of monopoles would then be by observing their effect on the luminosity distribution of neutron stars.

On the other hand, if the Parker limit on the interstellar flux is nearly saturated, we conclude that the cross section σ for monopole-catalyzed nucleon decay is smaller by at least eight orders of magnitude than estimated by Rubakov and Callan. This discrepancy could arise because their estimates are wrong, or because the correct unified theory is one to which their analysis does not apply - for example, one in which

"X-boson" exchange is baryon number conserving.

8 *CONCLUSIONS*

The discovery of a magnetic monopole, if genuine, has many implications. Among them are the following:

The monopole must be superheavy. If the monopole mass m is less than 10^{17} GeV, there is no reason to doubt the validity of the Parker limit, Eq. (25). Therefore, the only credible explanation for the apparently large local flux is the solar cloud scenario. But the sun can act as an efficient monopole collector only if the typical velocity of a monopole incident on the solar system is comparable to or smaller than the solar escape velocity, about 2×10^{-3}c. In view of Eq. (20), this means that m cannot be much less than 10^{16} GeV.

Since no astrophysical process is energetic enough to produce superheavy monopoles, any monopoles present today must have been produced in the very early universe. That any exist at all is evidence that the universe was once *extremely* hot.

The discovery of a monopole will have an important impact on cosmology. The monopole abundance will join the helium abundance and the baryon abundance as a number which must be explained by a realistic cosmological scenario. It appears that this will be a very severe constraint.

If the local monopole flux is as large as suggested by the Cabrera event, then either monopoles play an unexpected active role in the dynamics of the galactic magnetic field, or the monopole flux in the solar system is much larger than that in the galaxy at large. The astrophysical consequences of either alternative will be interesting to explore.

The existence of monopoles poses a welcome challenge to experimenters, for to further elucidate the properties of monopoles will continue to require ingenious new experimental methods.

Finally, from the perspective of particle physics, the mere existence of a magnetic monopole is enormously significant, because it confirms a fundamental prediction of grand unification. If the mass of the monopole can be measured, we will learn, at least in order of magnitude, the fundamental symmetry breaking scale M_{GUT} at which electrodynamics becomes truly united with the other particle interactions. Possibly, we will also be able to learn this mass scale by measuring the proton lifetime, but if M_{GUT} is only slightly larger than suggested by the standard estimates based on the desert hypothesis, proton decay will be extremely difficult to

observe. Then a measurement of the monopole mass may be the only way to determine M_{GUT} by doing a low energy experiment.

Whether a monopole has in fact been discovered remains to be verified. If so, then for the above reasons, and more, we are all very lucky indeed.

ACKNOWLEDGEMENTS

It is a great pleasure to extend thanks to the organizers, Gary Gibbons and Stephen Hawking, for the opportunity to attend the Nuffield Workshop, and to all the participants who helped to make it such a spectacular success.

This work was supported in part by the National Science Foundation under Contract Number PHY77-22864, and by the Alfred P. Sloan Foundation.

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