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COSMOLOGICAL AND ASTROPHYSICAL IMPLICATIONS OF MAGNETIC MONOPOLES*

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ABSTRACT

Among Dirac's many contributions to modern physics is the idea that charge quantization is natural in a theory with magnetic monopoles. The existence of magnetic monopoles would have drastic effects on the evolution of the universe, on galactic magnetic fields, and perhaps on the x-ray luminosity of neutron stars. In this talk I will review some astrophysical implications of massive magnetic monopoles.

In 1931, Dirac showed that the quantization of electric charge follows in any theory which also includes magnetic charge [1]. In such theories, the electric charge, e , and magnetic charge, g , are quantized according to the "Dirac quantization condition"

$$eg = n/2 \quad (n \text{ integer}) \quad . \quad (1)$$

As originally introduced by Dirac, the monopole was simply a new dynamical degree of freedom to be added to the system, and all the monopole properties, such as mass, spin, electric charge, etc. were free parameters.

This situation changed in 1974, when 't Hooft and Polyakov [2,3] demonstrated that monopoles must occur in certain classes of gauge theories. Among the classes of gauge theories with monopoles are the grand unified theories (GUTS), which attempt to unify the strong and electroweak interactions. In these theories, all the monopole properties are calculable. In this talk, I will consider only the monopoles in grand unified models based on SU(5). The specialization to SU(5) is for convenience only; the same conclusions would obtain in any GUT.

The mass of the GUT monopole is related to the scale of the breaking $G \rightarrow G' \otimes U(1)$, where G is the grand group. In SU(5), this would correspond to the mass scale for the breaking $SU(5) \rightarrow SU(3) \otimes SU(2) \otimes U(1)$. The limit on the proton lifetime requires this scale to be greater than about 10^{14} GeV. The mass of the monopole is roughly this scale divided by α , or about 10^{16} GeV. This enormous mass (10^{-8} g) prevents creation of monopoles in accelerators. Only in the early universe can the energy be found to create the monopoles.

There are two sources of monopole creation in the early universe; thermal production, and spontaneous production in the phase transition [4,5]. As spontaneous production dominates in the standard cosmology, I will ignore thermal production.

The key ingredient in spontaneous production is the fact that at high temperatures, thermal effects of the ambient background gas should have restored the symmetry. That is, at temperatures much greater than 10^{15} GeV, $\langle\phi\rangle = 0$, where $\langle\phi\rangle$ is the vacuum expectation value of the Higgs field responsible for the breaking $SU(5) \rightarrow SU(3) \otimes SU(2) \otimes U(1)$. Since monopoles exist as knots in $\langle\phi\rangle$, in the symmetric phase ($\langle\phi\rangle = 0$) there are no monopoles. At some critical temperature, $T_c \cong 10^{15}$ GeV, spontaneous symmetry breaking occurs, and monopoles will be formed. The number of monopoles formed depends on the distance over which the Higgs field can be correlated, which in turn, depends upon the size of the causal horizon.

The causal horizon, d_H , in the standard big bang model is given by

$$d_H = 2ct \cong m_{Pl}^{-1} t^2 \quad (2)$$

where t is the time since the bang, which can be expressed in terms of temperature (T) and the Planck mass (m_{Pl}) in the standard model. The Higgs field cannot be correlated over distances larger than d_H , and the finiteness of the correlation length leads to the production of monopoles. The number of monopoles produced may be calculated by considering three points, A, B, and C separated by a distance greater than d_H . At each point, we can represent the orientation of $\langle\phi\rangle$ in group space by a vector. As the distances AB, AC, BC are greater than the causal horizon, the direction in group space of $\langle\phi\rangle$ at the three points are independent. There exists a finite probability, about 10%, that any given orientation of the vectors will correspond to a nontrivial topology, i.e., correspond to a monopole [6]. Therefore, the expectation is that on average one monopole per 10 horizon volumes should be created (and an equal number of antimonopoles). This leads to the creation of a number density of monopole-antimonopole pairs of

$$n_M = n_{\bar{M}} \cong 0.1 d_H^{-3} \cong 10^3 T_c^6 / m_{Pl}^3 \quad (3)$$

It is convenient to compare this number density to the photon number density at $T = T_c$, $n_Y \cong T_c^3$

$$\frac{n_M}{n_Y} = \frac{n_{\bar{M}}}{n_Y} \cong 10^3 \frac{T_c^3}{m_{Pl}^3} \cong 10^{-9} \quad (T_c = 10^{15} \text{ GeV}). \quad (4)$$

After creation of the monopoles, monopole/antimonopole pairs can annihilate. This annihilation causes the monopole density to decrease as (ignoring monopole/antimonopole creation in collisions)

$$\frac{dn_M}{dt} = \frac{dn_{\bar{M}}}{dt} = - \langle n_M n_{\bar{M}} \sigma_A |v| \rangle - 3 \frac{\dot{R}}{R} n_M, \quad (5)$$

where σ_A is the $M\bar{M}$ annihilation cross section. The classical calculation of σ_A involves monopole-antimonopole capture into a bound state, with subsequent emission of radiation until the eventual annihilation [4,5,7]. The solution to (5) results in a "freeze out" density of monopoles of about

$$\frac{n_M}{n_Y} = \frac{n_{\bar{M}}}{n_Y} \sim 10^{-10}. \quad (6)$$

The ratio in (6) is roughly constant during the subsequent evolution of the universe. Therefore, today the monopoles would contribute an energy density of

$$\rho_{MM} = n_M n_{\bar{M}} \sim 10^{-10} m_M n_Y. \quad (7)$$

There are about 400 cm^{-3} photons in the universe today, and if the monopole mass is 10^{16} GeV (10^{-8} g), the monopoles would contribute an energy density of

$$\rho_{\text{MM}} \cong 10^{-15} \text{ g cm}^{-3} \cong 10^{14} \rho_c \quad (8)$$

where ρ_c is the critical density. Since observationally we know the total energy density of the universe must be less than $2\rho_c$, the energy density in (8) is about 14 orders of magnitude too large. Therefore, there must be some way either to avoid making so many monopoles, or to efficiently annihilate the monopoles.

The obvious lesson is that we are missing something very fundamental in the simple picture of the early universe we have just discussed. Below we discuss some proposals that have been made to alleviate the monopole problem.

The monopoles are formed in the phase transition; if one could avoid the phase transition, monopoles would not be produced. One possible way to avoid the phase transition is to assume that the universe had a maximum temperature, T_{MAX} , less than the critical temperature, T_c . This assumption has the unwanted feature that baryon production is difficult, since temperatures of the order $T_c \sim m_X$ are necessary to make baryons. There may be a narrow range for T_{MAX} , where $T_{\text{MAX}} < T_c$, and T_{MAX} is still large enough to produce baryons; but unless there is some physical reason for T_{MAX} to be in that narrow range, this solution cannot be taken seriously. One possible physical reason for $T_{\text{MAX}} \lesssim T_c$ can arise in grand unified models which are not asymptotically free [8]. Such asymptotically non-free models are considered ugly on aesthetic grounds, but quite naturally arise in complicated GUTS [8].

Another possible way to prevent the universe from being in the symmetric state, is to assume that there is a large fermion asymmetry that prevents high temperature restoration of symmetry [9]. Such an initial large fermion number may have further implications for cosmology, e.g., for the neutrino number of the universe [10].

One possibility in enhancing annihilation is to assume that the monopoles are clumped, and n_M appearing in (5) is larger than the value obtained in uniform expansion. The gravitational attraction of monopoles provides just such a mechanism. The possibility that monopoles form bound objects and annihilate was suggested by Preskill [5], and examined in detail by several groups [7,11]. All have concluded that the mechanism of gravitational clumping cannot solve the monopole problem.

Another possibility is that when the monopoles and antimonopoles form, they are connected by strings, and are confined [12]. A basic assumption in (5) is that the initial states are uncorrelated in the scattering. If monopoles are connected to antimonopoles by strings, the initial state is correlated, and the annihilation rate will be much enhanced. Although the physics behind the motivation is somewhat uncertain, there is at least some reasons to believe in monopole confinement since monopole confinement could be an artifact of the non-Abelian nature of the monopole.

The number of monopoles created in the transition is proportional to T_c^3/m_{pg}^3 . If the critical temperature is less than about 10^{10} GeV, an acceptable monopole density would result. One method of postponing the phase transition involves supercooling [13,14], and was the original motivation of the inflationary universe. Another possibility is an intermediate symmetry as proposed by Langacker and Pi [15], where the U(1) appearance is postponed until $T < 10^{10}$ GeV.

In conclusion, the dearth of monopoles in the universe gives us very important information about the early universe. Unfortunately, it is not clear how to interpret the information. Perhaps one of the scenarios for monopole suppression discussed above is the solution to the "monopole problem," but it is just a likely that the solution has not yet been found. Some of the solutions discussed above get rid of all the monopoles. Some of the solutions get rid of some of the monopoles. The obvious next step is to look for monopoles today. The next section discusses limits on the present monopole flux, both astrophysical limits and experimental limits.

So far we have seen that massive magnetic monopoles are predicted to exist in grand unified theories, and should have been copiously produced in the big bang. In fact, the predicted density of monopoles is so large that some mechanism must either suppress their production, or efficiently reduce their number after creation. If monopoles could be detected, knowledge of the present monopole flux would help in determining the suppression mechanism.

Before discussing terrestrial experiments, it is useful to discuss some astrophysical limits. The first limit comes from the mass density of the universe. The "critical density" for closure of the universe is (H_0 is the Hubble constant) $\rho_c \sim 2 \times 10^{-29} \text{ g cm}^{-3}$. We know observationally that the energy density of the universe is less than $2\rho_c$. This implies that the average number density of monopoles, $\langle n_M \rangle$, is limited by requiring that the energy density of the monopoles, $\rho_M = \langle n_M \rangle m_M$ is less than $2\rho_c$.

$$\langle n_M \rangle \lesssim 4 \times 10^{-21} \frac{10^{16} \text{ GeV}}{m_M} \text{ cm}^{-3} \quad (9)$$

In order to compare with experiments, we must form a flux from the density. If we assume the monopoles are completely uniform throughout the universe, they would be cold, and the relevant velocity would be the velocity of our galaxy relative to the cold monopoles. This velocity is our peculiar velocity relative to the 3K background radiation [16], $v_M \cong 10^{-3} c$. Therefore, the flux of monopoles in the universe must be

$$\langle F_M \rangle_U \lesssim \langle n_M \rangle_U v_M \quad (10)$$

$$\lesssim 10^{-14} \frac{10^{16} \text{ GeV}}{m_M} \frac{v_M}{10^{-3}} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} .$$

It is perhaps more reasonable to assume that the monopoles are clumped, and that their density in our galaxy is enhanced over the average density throughout the universe, as are the protons. In that case, the relevant mass density limit is roughly $10^6 \rho_c$, and the relevant velocity would be the galactic virial velocity, again about $10^{-3} c$. The limit in this case is

$$\langle F_M \rangle_G \lesssim 10^{-9} \frac{10^{16} \text{ GeV}}{m_M} \frac{v_M}{10^{-3}} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} . \quad (11)$$

The best astrophysical limit comes from the observation of large-scale galactic magnetic fields. The original argument is due to Parker [17]. He argued that if the galactic magnetic fields are due to currents, then monopoles drain energy from the field as they are accelerated. The rate of extracting energy from the magnetic field is $F_M B_G$, where B_G is the galactic magnetic field ($B_G \cong 10^{-6}$ gauss). The energy in the magnetic field is $B_G^2/8\pi$, and this energy will be drained on a timescale $\tau_B = B_G^2/32\pi^2 F_M B$. In order for magnetic fields to survive, this timescale must be less than the

timescale for regeneration of the magnetic field, which is the order of the galactic rotation time, about 10^8 years [17]. The requirement $\tau_B \gtrsim 10^8$ years requires

$$F_M \lesssim 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} . \quad (12)$$

Equation (12) has become known as the "Parker limit." More detailed studies [18] have closed several loopholes in the simple argument given above, and have concluded that the limit (12) is probably good to an order of magnitude for reasonable values of the monopole mass. It is possible to evade the Parker limit if the monopoles themselves are the sources of the magnetic field [18,19]. This scenario is hard to imagine, since it needs large magnetic charge fluctuations. However, it potentially weakens the Parker limit by about 5 orders of magnitude.

The uncertainty in the astrophysical limits is easily matched by the uncertainties in terrestrial searches. The largest source of uncertainty comes from the difficulty in calculating the energy loss from slowly moving monopoles. For a discussion of the difficulties of such a calculation, see Ahlen and Kinoshita [20]. They find an energy loss for massive, slowly moving monopoles in silicon of $dE/dx \approx 50 \beta \text{ GeV cm}^{-1}$ for $\beta \leq 10^{-2}$, where β is the monopole velocity.

All reported experiments that detect monopoles by ionization depend on calculations of the monopole ionization. Although different experiments use slightly different values for the ionization, it is still interesting to compare some quoted limits:

$$F_M \lesssim 10^{-10} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (\beta \gtrsim 3 \times 10^{-3}) \quad (13a)$$

$$F_M \lesssim 3 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (3 \times 10^{-4} \leq \beta \leq 10^{-3}) \quad (13b)$$

$$F_M \lesssim 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (2 \times 10^{-4} \leq \beta \leq 3 \times 10^{-2}) \quad (13c)$$

$$F_M \lesssim 2 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (10^{-2} \lesssim \beta) \quad (13d)$$

$$F_M \lesssim 3 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (10^{-3} \leq \beta \leq 10^{-2}) \quad , \quad (13e)$$

where the limits quoted in (13a) ... (13e) are given in refs. [21] ... [25], respectively.

The cleanest way to look for monopoles is the superconducting search done by Cabrera [26]. This method is based on the change in the macroscopic quantum state of a superconducting ring when a magnetic charge passes through the ring. The magnetic flux through the superconducting ring changes the current, which is detected by a SQUID. This method is clean, since it is independent of the monopole mass, monopole velocity, monopole electric charge, and energy loss calculations. Cabrera has reported a limit [26]

$$F_M \lesssim 6 \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad , \quad (14)$$

and a candidate event. If we assume the candidate event was the actual detection of a magnetic monopole, the flux of $6 \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ represents the actual monopole flux.

Although one event does not give unequivocal evidence for the existence of magnetic monopoles, it is interesting to assume this event is the result of a flux given in (14) and examine the consequences. First, it is obviously in conflict with the ionization searches discussed above. This

would mean that either the monopoles are very slow ($\beta \ll$ galactic virial velocity) or the ionization calculations are in serious error. The Cabrera flux is also in serious disagreement with the Parker limit. Either we do not understand galactic magnetic fields, or the monopole flux on earth is much different than the average galactic flux. The latter possibility has been examined by Dimopoulos, Glashow, Prucell and Wilczek [27]. They suggested that there is a "cloud" of monopoles orbiting the sun, which enhances the monopole flux at the earth by a factor of 10^5 relative to the average galactic flux. In this manner it may be possible to reconcile the Cabrera flux with the Parker limit.

In conclusion, there is one hint that monopoles exist in our galaxy. If this hint proves correct, it may have drastic implications for our understanding of galactic magnetic fields.

Two dramatic predictions of GUTS are proton decay, and the existence of magnetic monopoles. Recent model calculations by Rubakov [28], Callan [29], and Wilczek [30] have suggested that proton decay in the presence of a monopole occurs at a much faster rate than one might guess on dimensional grounds.

A naive dimensional estimate of the cross section $pM \rightarrow MX$, where X denotes the proton decay products, might be $\sigma_{\Delta B} = m_M^{-2}$, where m_M is the monopole mass. However Rubakov and Callan have argued that the cross section is independent of the mass of the monopole, and it is related instead to the mass scale of color confinement, about 1 GeV. We shall parameterize the cross section for monopole-induced proton decay by a mass scale Λ :

$$\sigma_{\Delta B} = \frac{\pi}{\Lambda^2} \cong \frac{10^{-27}}{\Lambda_{\text{GeV}}^2} \text{ cm}^2, \quad (15)$$

where $\Lambda_{\text{GeV}} = \Lambda/1 \text{ GeV}$. If the conjecture of Callan and Rubakov is correct, then $\Lambda_{\text{GeV}} \cong 1$.

There are two obvious questions to be asked about monopole-induced proton decay. First, does it open up new methods for detecting cosmic monopoles. Second, does monopole-induced proton decay have any important astrophysical consequences. The answer to both questions is yes!

If monopoles induce proton decay while traversing a proton decay detector, then proton decay detectors would make the most sensitive monopole telescopes. A preliminary study by the Irvine-Michigan-Brookhaven proton decay collaboration has concluded that with minor modifications, the detector would have a sensitivity to a monopole flux of about $10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, if $\sigma_{\Delta B} \approx 10^{-27} \text{ cm}^2$ [31]. This is several orders of magnitude better than the limits in (13).

If monopoles induce proton decay, they would have a drastic effect on the x-ray luminosity of neutron stars [32,33]. By using the limit on the neutron star luminosity, it is possible to place a limit on the product of the galactic monopole flux and baryon violating cross section, which suggests that the phenomena of monopole-induced proton decay is not likely to be detected terrestrially.

Neutron stars are believed to be plentiful in our galaxy [34], and to be as old as the galaxy itself. During the lifetime of the neutron star, the neutron star would have been subjected to a galactic monopole flux F_M . This resulted in a number of neutron star/monopole collisions given by

$$N_M = \frac{2\pi}{3} F_M A_c t_{NS} , \quad (16)$$

where t_{NS} is the lifetime of the neutron star, and A_c is the "capture" area given by

$$A_c = R_{NS}^2 \frac{1 + 2M_{NS} G/v_M^2 R_{NS}}{1 - R_S/R_{NS}} . \quad (17)$$

In (17), M_{NS} and R_{NS} is the mass and radius of the neutron star, v_M is the galactic velocity of the monopole, and R_S is the Schwarzschild radius of the neutron star. Putting in values of $M_{NS} = 1 M_\odot$, $R_{NS} = 10^6$ cm,

$$N_M = 10^{36} F_M (\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}) . \quad (18)$$

The monopole will be trapped in the neutron star, mainly through energy loss in scattering with electrons [20,33]. This results in an energy loss of

$$\frac{dE}{dx} \sim \beta 10^{11} \text{ GeV cm}^{-1} , \quad (19)$$

where β is the monopole velocity in the star ($\beta \approx 10^{-1}$ is escape velocity). If $\beta \geq 10^{-1}$, the monopole will lose about 10^{16} GeV traversing the star (if $\beta \leq 10^{-1}$ the monopole must be trapped). The initial energy of the monopole in the galaxy was

$$E_0 = \frac{1}{2} m_M v_M^2 \quad (20)$$

$$\approx 10^9 \frac{m_M}{10^{16} \text{ GeV}} \left[\frac{v_M}{10^{-3}} \right]^2 \text{ GeV} .$$

Therefore, if the monopoles have typical virial velocities of 10^{-3} , monopoles of mass less than 10^{22} GeV ($10^3 m_{\text{Pl}}$) will be trapped.

The monopoles trapped in the star catalyze nucleon decay, and release energy at a rate

$$L_M = m_N n_N \sigma_{AB} |v|$$

$$\approx 8.5 \times 10^{17} \Lambda_{\text{GeV}}^{-2} \text{ erg s}^{-1} \text{ monopole}^{-1}, \quad (21)$$

where m_N is the nucleon mass, n_N is the nucleon density, and we have used $|v| \approx 10^{-1}$, the nucleon Fermi velocity.

Combining (18) and (21), the energy produced in the neutron star by monopole-induced nucleon decay is

$$L = 2 \times 10^{54} \Lambda_{\text{GeV}}^{-2} F_M (\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}) \text{ erg s}^{-1}. \quad (22)$$

This luminosity is the total luminosity, which in general may be emitted as photons and neutrinos. The best limit on the photon luminosity comes from recent surveys for serendipitous x-ray sources [35]. These surveys could detect an x-ray luminosity of $L_Y = 10^{31} \text{ erg s}^{-1}$ at a distance of 1 kpc [35]. Estimates based on the current pulsar birth rate in the solar neighborhood predict there should be an old neutron star density of $n_{\text{NS}} \geq 4 \times 10^{-3} \text{ pc}^{-3}$. Therefore, it is reasonable as an extremely conservative estimate, to take $10^{31} \text{ erg s}^{-1}$ as the maximum luminosity of old neutron stars.

The relationship between the x-ray luminosity and the total luminosity depends on the structure of the neutron star. The smallest L_Y/L^0 ratio results for zero surface magnetic field, and for pion condensation in the neutron star interior. In this case, $L_Y \geq 10^{31} \text{ erg s}^{-1}$ corresponds to a

total luminosity of about $10^{33} \text{ erg s}^{-1}$ [36]. It is also important to note that a photon luminosity of $10^{31} \text{ erg s}^{-1}$ corresponds to a surface temperature of $T_S = 0.04 \text{ keV}$. About 80% of the energy radiated at this temperature will be in the window of the Einstein satellite.

A maximum total luminosity of $10^{33} \text{ erg s}^{-1}$ requires

$$F_M(\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}) \Lambda_{\text{GeV}}^{-2} < 5 \times 10^{-22} \quad . \quad (23)$$

Therefore, if monopoles catalize proton decay at a strong rate ($\Lambda_{\text{GeV}} \approx 1$) the flux limit of (23) is about 6 orders of magnitude better than the Parker limit discussed in the previous section. This limit is also 6 orders of magnitude below the possible limit for detection reported by the IMB group.

Conversely, if proton decay detectors do see monopoles, something very basic is very wrong in our understanding of neutron stars.

Not only do magnetic monopoles provide a natural explanation for charge quantization, but they must exist in grand unified theories. In such theories, the monopole is very massive, and the early universe is probably the only source for production.

The early universe should have provided a plentiful supply of monopoles. In fact, the simplest prediction one might make results in a monopole density 10^{14} orders of magnitude too large. This important cosmological probe of the early universe tells us that either the simple picture of unification, or the simple picture of the early universe is seriously wrong. There have been several proposals to solve the monopole problem, they all have important implications for cosmology, and could potentially alter our picture of the early universe. Detection of a monopole would be strong evidence that the universe was once at a temperature greater than 10^{15} GeV .

There have been several recent terrestrial searches for massive magnetic monopoles. One experiment [26] can be interpreted as detection of a monopole. If this experiment is confirmed, then the flux of magnetic monopoles would be many orders of magnitude too large for us to understand the existence of galactic magnetic fields.

There are theoretical indications that the cross section for monopole-induced proton decay is a strong cross section. If this is true, then a galactic monopole flux greater than $10^{-22} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ would result in an enormous x-ray luminosity for neutron stars. Therefore, a detection of monopoles on earth would not only mean that galactic magnetic fields do not exist, but neutron stars do not exist.

Not only do magnetic monopoles provide a probe of particle physics, but potentially are a great source of information in astrophysics.

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