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DOWN TO EARTH SPECULATIONS ON GRAND UNIFICATION MAGNETIC MONOPOLES

R. A. Carrigan, Jr.
Fermi National Accelerator Laboratory, Batavia, Illinois, 60510

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Abstract

Elementary particle grand unification theories admit the possibility of very massive magnetic monopoles, but with standard cosmology give too many monopoles. Massive monopoles are affected both by gravity and magnetism, requiring reassessment of existing monopole searches. Monopoles inside the earth would be able to annihilate with each field reversal. Monopole to baryon ratios of 10^{-28} could still account for a fraction of the earth's internal heat. Implications for lunar magnetism and ice ages are considered.

Recent grand unification particle theories such as SU(5) allow the existence of massive 't Hooft magnetic monopoles[1]. These theories make several predictions including the Weinberg angle in weak interactions, the proton lifetime, mass relations between quarks and leptons and the baryon assymmetry in the universe. Polyakov and 't Hooft[2] independently first observed that theories such as SU(5) with an imbedded U(1) symmetry could contain a solution that corresponds to an ordinary magnetic monopole away from the center of the particle. These theoretical developments have been a source of intense interest in the last years[3]. Goddard and Olive[4] have noted that this classical approach can reproduce the Dirac charge quantization condition[5] by associating a massive vector boson with the theory. Bogomol'nyi[6] has found a lower limit on the monopole mass in such a theory of $M > 4\pi M_V/g^2$ where M_V is the mass of a vector boson and g^2 is a dimensionless coupling constant. If M_V is associated with the intermediate vector boson of weak interactions, g^2 is equal to α, the fine structure constant and the Bogomol'nyi bound is on the order of 10 TeV, well above the reach of any accelerator facilities that will be available before the late 1990's.

Many grand unification theories are characterized by the presence of super heavy colored vector bosons with a mass that sets the unification mass scale and is on the order of $M_X = 10^{14}$ GeV. In SU(5) the lower bound on this mass is set by the present lower limit on the lifetime of the proton and is on the order of $M_x^4 = 10^{-4} \tau_p m_p^5 c/\hbar$ where τ_p is the lifetime bound on the proton (currently around 2×10^{30} years), and m_p is a mass near the mass of the proton[7]. The mass of a grand unification magnetic monopole (GUMM) is set by the Bolgomol'nyi bound with the related coupling constant on the order of 1/50[8]. Therefore GUMMs are expected to have masses on the order of 10^{16} GeV. This mass of 0.02 micrograms is extraordinarily large for a fundamental particle.

Such massive particles might have been produced in the big bang in the early universe. Preskill[9] and others[10] have examined this possibility in some detail. Preskill has shown that for standard cosmology and plausible grand unification models that the number of GUMMs would be close to the number of baryons even now in the universe. The evidence is clearly against this in our own corner of the universe since magnetic monopoles are not an ordinary factor in our daily lives. Several suggestions have been made for possibilities to circumvent Preskill's paradox. Preskill, along with Guth and Tye[11], have suggested that a strongly first order phase transition could lower the GUMM to photon (and thereby baryon) ratio but not make it zero. Langacre and Pi[12] have shown that introducing spontaneous breaking of electromagnetic gauge invariance can eliminate the monopoles but results in charge non-conservation. Lazarides and Shafi[13] have noted that certain grand unification group structures, which do not include the ones ordinarily considered, can eliminate the magnetic monopoles. Fry and Schramm have asked whether the conditions for statistical equilibrium in the cosmological models really exist with the monopoles present.[14] The grand unification-standard cosmology system is then faced with a paradox that can be moderated or even turned off but with some difficulty. Of course grand unification remains to be established as a fundamental relevant theory and standard cosmology appears to leave some room for adjustments. However, in view of this paradoxical situation it is important to try to better understand the limits on the existence of massive magnetic monopoles.

Consider the history of a massive magnetic monopole in the universe. It could be born either in the big bang or by production in a cosmic ray interaction. However it does not appear possible to produce particles with the masses of GUMMs in cosmic ray collisions. Bludman and Ruderman[15] note that the threshold for production of mass M with ordinary particles is $E >> 2\ M^2c^2/m_N$ where m_N is the mass of the target nucleus. Present upper bounds on cosmic ray energies limit masses that can be produced by cosmic rays to less than $3 * 10^5$ GeV. After the GUMM is born in the primordial fireball and survives annihilation it can eventually be accelerated to energies of the order of 10^{11} GeV by galactic magnetic fields[16] on the order of $3 * 10^{-6}$ gauss acting over distances of 10^{21} cm[17]. These are non-relativistic energies for massive GUMMs so that previous conventional wisdom on energy loss of relativistic monopoles and on transit times must be used with discretion.

While no magnetic monopoles have been found[18], several possibilities have been suggested for monopole detection. Relativistic monopoles with a magnetic charge around the Dirac charge are expected to produce heavy ionization when passing through matter. On the other hand, for small β the energy loss drops as the monopole slows down. Ahlen has treated monopole energy loss in some detail[19]. Care must be taken if triggered, timed counters are used to record the passage of the monopole. For example in a typical monopole search device[20] a Dirac monopole would typically be accelerated for 50 cm in an 80 kg field to gain an energy of 80 BeV and then detected with counters spaced 25 cm apart and a timing window of 20 ns. This window implies a minimum beta of 0.04. The upper limit for mass that can be detected by such an apparatus is 10^5 GeV.

Monopoles passing through a coil should produce an induced voltage since a net magnetic flux goes through the loop. This technique, originally suggested by Tassie and by Vant-Hull[21], has been exploited by Ross et al.[22] to search for magnetic monopoles trapped near the surface of the moon. The technique has the fortunate aspect that it is insensitive to monopole mass and somewhat insensitive to magnetic charge. On the other hand as with many other approaches it is affected by the circumstances of the monopole trapping in the sampled volume. For the moon's surface it has been demonstrated that the monopole to baryon ratio is less than $3 * 10^{-28}$.

The presence of free magnetic monopoles in any number has a profound efect on large scale magnetic fields. Parker[17] in reviewing these effects notes that monopoles would dissipate and neutralize magnetic fields. For a Dirac monopole Parker suggests that this places a limit on the monopole to baryon ratio for the galactic system of $2 * 10^{-26}$. Parker's calculation presumes relativistic monopoles. For non-relativistic GUMMs the limit should probably be reduced by 100 to $2 * 10^{-24}$ because the monopole flux decreases as β . Limits due to non-dissipation of the solar and terrestrial fields are less stringent and the galactic limit is less stringent than the lunar search.

A primordial magnetic monopole is subjected to several different forces. Magnetic fields from cosmological sources (galactic, stellar, terrestrial), ferromagnetic and diamagnetic materials and other magnetic monopoles will all act on it. Gravitational forces and cosmological expansion will influence it. Finally interactions will occur with ordinary electronic matter through processes such as ionization.

Many analyses of magnetic monopole behavior on a macroscopic scale only consider the magnetic effects. It has not generally been recognized that the force of gravity will approach the magnitude of typical cosmical magnetic fields for monopoles with masses in the range expected for the GUMMs (note, however, Langacker's comment[12]). For example the gravitational energy acquired by a GUMM with a mass of 10^{16} GeV falling into the galactic disc is 10^{10} GeV while the energy gained in passing through a typical galactic magnetic field fluxuation distance (300 light years or

$3 * 10^{20}$ cm) is $2 * 10^{10}$ GeV. It is interesting to note that a GUMM with this energy could easily go deep into or even pass through the earth although it might be stopped by ionization in going into the sun. The magnetic force at the galaxy is five hundred times larger than the gravitational force but the gravitational force acts over a much larger distance. Similarly the gravitational energy from solar or terrestrial sources exceeds the energy acquired from the corresponding magnetic field. For example, for the earth the gravitational potential energy at the surface is on the order of 10^7 GeV, while the magnetic energy is $5 * 10^3$ GeV. Somewhat similar conditions are obtained for the sun. For a magnetic dipole earth acting in a repulsive sense with a force that goes as $1/r^3$ (not a realistic approximation in this case) the magnetic and gravitational forces are in equilibrium at $R = 0.18\ R_e$. This is well inside the radius of the molten core ($R_c = .55\ R_e$) and even inside the solid core radius ($R_{sc} = 0.19\ R_e$). On the other hand at a particle level the ratio of gravitation to magnetic self energy, $(2\alpha \sqrt{G}\ M/e)^2$, is much less than one.

In a sufficiently dense material a GUMM will eventually be thermalized. It will then move to an equilibrium position where the magnetic, gravitational, and other forces are in equilibrium. In a dipole earth this would be on a line with the opposite terrestrial magnetic pole and the gravitational center. The same situation holds true for magnetic fields generated by currents. If the dipole is in a fluid it will be able to move relatively freely. In a solid it may have to move by what amounts to a series of lattice jumps as suggested by Amaldi et al.[23]

Since gravitational forces and magnetic forces are intermingled and GUMMs will be attracted to opposite cosmical poles one must be quite cautious about where one looks for monopoles and particularly GUMMs. For example consider a heavy primordial monopole that accretes in equilibrium with the baryonic material of the earth. It will move preferentially closer to the center of the system because of the presence of a terrestrial magnetic field. This means that the earth's surface is probably a poor place to look for relic GUMMs. If a large number of monopoles were present they could even partially neutralize the terrestrial field along the line suggested by Parker.

Now it is known that the magnetic field of the earth reverses irregularly[24] with epochs of one field direction lasting on the order of one million years interspersed with occasional reversal events of somewhat shorter duration. The time to reverse the field is on the order of 1000 years. The reversal process is apparently quite turbulent. The earth's magnetic field is due to a convective dynamo in the fluid core driven by the heat in the earth's center. The interior field is complex. The dipole field lines flow into the core and then spiral around the earth's axis of rotation. This results in much larger axial than poloidal magnetic fluxes inside the core. Parker suggests that the axial fields might be on the order of 100 gauss while the poloidal fields are on the order of five gauss. Superimposed on this distribution is further turbulence due to convective cells within the dynamo.

When the earth's field reverses GUMMs of one polarity in equilibrium would have to move to the equilibrium positions previously held by the opposite polarity. In the process some of them would pass close enough to poles with the opposite polarity to attract, bind and then annihilate. Annihilation would result in the release of an extraordinary amount of energy. What, then, would be the contribution of such an energy source to the terrestrial heat inventory?

It seems fair to say that the heat generation inside the earth is not completely understood.[25] Heat comes from both gravitational forces (including some of the energy due to the original planetary accretion) and radioactivity in the interior of the earth. It is believed that differentiation processes concentrate radioactive materials selectively in the silicates which rise to form the earth's crust. This has led to the view that much of the earth's radioactivity is in the mantle or the crust. Estimates of average heat flow per unit area over the surface area have been revised upward in the last decade by approximately 20% as the contribution of the ocean basins was better understood. The average heat flow at the surface is $1.5 * 10^{-6}$ cal/cm^{2}sec ($4 * 10^4$ GeV/cm^{2}sec). The total heat output is $3 * 10^{20}$ ergs/sec ($2 * 10^{23}$ GeV/sec). (For contrast this should be compared to the expected upper limit of 10^9ergs/sec or $6 * 10^{11}$ GeV/sec from proton decay inside the earth.) This is about one part in five thousand of the solar heat flux incident on the earth. Some geoscientists argue that the earth contains insufficient radioactivity to drive this heat flow while others maintain that it can be modeled with no radioactivity at all. In addition, the thermal properties of the material in the core under extremely high pressure are not well known. Clearly, then, understanding the relevant contributions to this heat flow is no easy matter.

A plausible assumption could be made that on the order of twenty-five percent of this heat generation could easily come from an unknown source such as the annihilation of massive magnetic monopoles. This corresponds to a heat source of $5 * 10^{22}$ GeV/sec. If it is assumed that a field reversal occurs once every 500,000 years then each reversal must supply $8 * 10^{35}$ GeV. If the annihilation energy is perfectly coupled to terrestrial material this requires the annihilation of 10^{20} GUMMs with masses of 10^{16} GeV. If the annihilation region is confined to the earth's core the annihilation event density is $n_a = 4 * 10^{-7}/cm^3$.

To get a monopole density for one polarity, n, from the annihilation density it is necessary to have a model for the monopole-antimonopole capture mechanism. One possible model is to assume that the core is uniformly filled with north and south monopoles. Monopoles are moving with some relative velocity v_D so they are wandering through the liquid core. When they approach within some distance r_a where the pole-antipole force is sufficiently strong to overcome external forces they will be drawn together and annihilate provided the angular momentum between the poles is small enough. For this model the annihilation event density is

$$n_a = \pi r_a^2 v_D t n^2 \qquad (1)$$

where t is the time during which annihilation takes place in the reversal.

Undoubtedly this picture is too naive. Turbulence and initial inhomogeneities would have to be present because the monopoles with opposite polarity would initially be separated. On the other hand as the reversal proceeds this equilibrium condition could exist over different smaller regions of the core. Under that circumstance the formula would still be satisfactory provided t represented the average time for some region to pass through equilibrium.

The monopole drift velocity could be influenced by several factors. For a monopole in thermal equilibrium with the liquid core at a temperature of $4000^{\circ}K$ the monopole thermal velocity is on the order of 10^{-2} cm/sec. Likewise the average mass drift velocity in the core is on the same order. On the other hand if an axial field of 100 gauss is present the characteristic monopole velocity might be 10^5 cm/sec based on extrapolating the Ahlen energy loss formula to low β values. With the complex coiled field geometry fully on, monopoles would move to equilibrium positions probably near the surface of the solid core or the inner surface of the mantle in about one year. If the reversal is turbulent, though, monopoles might slow substantially for some period even as they moved to regions where field lines had moved in again. At a velocity of 10^{-2} cm/sec the time to produce a homogeneous condition is on the order of 10^{10} seconds.

The capture distance, r_a , is sensitive to the size of the external forces such as gravity and the terrestrial magnetic field as well as relative monopole velocity. It also assumes that once the pair binds that a de-excitation mechanism permits them to annihilate. For characteristic forces that would be present (10^{-5} dynes) a plausible capture distance would be 10^{-5} cm.

For velocities on the order of 10^{-2} cm/sec, a capture distance of 10^{-5} cm, and a field reversal time of 1000 years the monopole density in the core to produce one fourth of the earth's heat is $n = 1.5 * 10^{-3}/cm^3$. This is equivalent to a monopole/baryon ratio at accretion of $2 * 10^{-28}$. The baryon number is taken for the entire earth rather than the core alone since it is presumed that monopoles were differentially attracted to the core.

This monopole density is easily sufficient to supply energy for on the order of 10^4 field reversals, equivalent to the age of the earth. Such a density would represent less than a 10% degradation of the earth's field with the details depending on the equilibrium configuration of the poles. If the concentration were higher an interesting situation would exist. For a constant dynamo strength over the life of the earth the average net field would rise with time as the monopoles annihilated. It should be noted that the monopole density could not be too much larger because the monopoles would then buck out the earth's field. Field dissipation due to magnetic currents, ala Parker, is less of a constraint.

These numbers all depend on the monopole mass. The density increases somewhere between the inverse of the fourth to the square root of the mass depending on the assumptions. Turbulence and inhomogeneities could also increase the density estimate. It seems difficult to attach any estimate of accuracy to such a speculative mechanism. Nevertheless the picture suggests that the monopole to baryon ratio in the earth is extremely small and consistent with the upper limit on the ratio observed at the surface of the moon.

There has been little theoretical consideration of the details of annihilation of pairs of GUMMs. Since the net available energy is much higher than any other mass including the masses of the leptoquarks it is likely that it would be partitioned more or less equally to many fundamental species such as leptoquarks, intermediate bosons, quarks and leptons. Energies of the individual fragments might be on the order of 10^{14} GeV. Some of the colored particles would have to be dressed before leaving the annihilation volume. Some of the particles, such as intermediate bosons, would decay quickly into muons and neutrinos. Thus a good fraction of the flux could come out as 10^{14} GeV muons and neutrinos. Muons of that energy lose nearly all of their energy by radiation rather than ionization.[26] If they lost energy only by ionization they would lose $5 * 10^{6}$ GeV in getting to the earth's surface.

However the muon radiation length in the earth is on the order of 1 km and the critical energy is 1 TeV so that the average range is 20 km. This means that muonic energy is dissipated quite close to the annihilation point.

At asymtotic energies[27] the neutrino cross section is expected to be on the order of $\sigma_\nu = 10^{-34}$ cm^2. At that cross section a substantial fraction of the neutrinos will interact before leaving the earth. These interactions will usually convert much of the neutrino energy to energetic muons and neutrinos.

The picture, then, is that during the thousand years or so of a field reversal much of the GUMM annihilation energy would be converted to local heat while the neutrino fraction would dissipate energy throughout the earth. Heat from the core moves by a convective diffusion process. Diffusion times go as the distance squared. Diffusion times from the core are on the order of the age of the earth. Some portion of the neutrino energy in a layer within a diffusion time of 1000 years of the surface (equivalent to roughly 10 km) would appear as an effective heat pulse during the field reversal. On the other hand, this is only 0.1% of the neutrino energy and substantially less of the total. However, that fraction appears in one five hundredth of the time so that it might constitute a thermal spike on the order of 0.01 to 0.1 of the average heat flow. This can be compared to the heat input needed to end an ice age.[28] Typically at the end of an ice age the sea water level rises around 40 m. This requires a heat input of $4 * 10^{34}$ GeV or the annihilation of $4 * 10^{18}$

GUMMs. Considering the small fraction of the neutrino energy that dissipates near the surface, GUMM annihilation seems to be insufficient to end a normal ice age. Event times of ice ages seem to be relatively less well established than magnetic reversals. The time of the recent Laschamp reversal event did occur at the peak of a glacial buildup. Note however that the period of the glacial phenomenon is much shorter than the characteristic period of field reversals and there is some evidence that many glacial effects are correlated with the earth's orbit parameters.[28]

Neutrinos from the core would be detectable during a reversal. If 100 neutrinos were produced per annihilation the muon flux from neutrino interactions within 20 km of the surface would be 10^{-10} muons/cm-sec. This would be sufficient to give 2 events per hour in a modern proton life time detector.

Similar effects would occur if GUMMs were present in other planetary bodies. The moon is the only other body for which satisfactory heat flow data has been established.[25] The moon has no dipole-like field at present[29], and there appears to be little, if any, molten core in the moon. Under these circumstances the relative heat flow should be lower than in the earth since any GUMM annihilation would have occurred in the very distant past. Unfortunately it is probably impossible to model the relative compositions and abundances with enough certainty to reach any conclusion. The moon's relic magnetism constitutes a tantalizing enigma. A field of 0.05 to 1 gauss would have been necessary to produce the magnetization.[30] Because of the low density of the moon and the parallel requirement that the core be small it is extremely difficult to model a lunar dynamo that would have produced the field.[31] If the moon accreted from a mix with a GUMM to baryon ratio five times larger than earlier suggested for earth and the GUMMs differentiated out into opposite poles during the process, their presence could explain a field on the order of 0.1 gauss. Some mechanism such as an external field from the earth or the solar wind would be needed to establish the north-south separation.

It appears, then, that even very small admixtures of GUMMs could produce noticeable changes in planetary conditions. On the other hand the search for massive primordial monopoles should continue. Logical search possibilities might include high density meteors from the cores of large asteroid bodies that have broken up. In this regard perhaps some reconsideration should be given to tracks in emulsion reported by H. H. Kolm et al.[32], from meteorites and deep ocean magnetic slurry. These tracks characteristically had track densities corresponding to a Dirac charge of 1/3. Viewed in retrospect this could be considered to be due to a massive, slowly moving monopole with concomitantly smaller energy loss. A later experiment by the same group established cross section limits that were smaller but the experiment was insensitive to masses greater than 10^4 GeV.

A new experiment is now being prepared by J. D. Ullman et al.[33] that will be sensitive to monopoles arriving at the surface of the earth with velocities in the range of 20 to 500 km/sec. The detection area will be 1 m^2.

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