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Massive magnetic monopoles: Indirect and direct limits on their number density and flux

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The existence of very massive magnetic monopoles is a necessary consequence of most unified theories of the strong, electromagnetic, and weak interactions. Estimates of their masses range from 10^{15} to 10^{17} that of a proton. Monopoles should have been produced in the "big bang" and survived to the present, either trapped in matter or in flight. By virtue of their huge mass, these monopoles might have eluded previous searches designed to detect monopoles with much smaller mass. I review the indirect limits which can be placed on monopoles because of the existence of large-scale galactic magnetic fields. I also review the experimental searches and reinterpret them to obtain limits for very massive monopoles. If the monopole masses are $\lesssim 5\times 10^{14}$ GeV/c^2, their concentration must be $\lesssim 10^{-27}$ monopoles/nucleon from searches for monopoles trapped in meteorites. This limit is several orders of magnitude lower than the astrophysical limits.

Many years ago, Dirac[1] showed that a free magnetic charge would have a strength which is an integer multiple of $g_1 = e/2\alpha$ in cgs units, where α is the fine-structure constant and e the electron charge. Since then numerous experimental searches have been conducted for magnetic monopoles at high-energy accelerators and in cosmic rays, either in flight or trapped in matter.[2] These searches were unsuccessful and interest in monopoles waned. Recently, however, the "rules" for the search changed drastically when it was realized that monopoles might exist with a mass $\gtrsim 10^{15}$ that of the proton, i.e., $Mc^2 \gtrsim 10^{15}$ GeV.[3–6] Monopoles of such huge masses could not be produced at any conceivable man-made accelerator, and are far beyond the range of masses that could be produced by the highest-energy cosmic rays ever observed. They should, however, have been produced, perhaps abundantly, in the big bang.[3] If so, their magnetic charge presumably guarantees their survival to the present epoch, except for the possibility of monopole-antimonopole annihilation.

The existence of massive magnetic monopoles seems to be a necessary consequence of grand unified theories,[4–6] which seek to unify the strong, electromagnetic, and weak interactions of particles. Generally these theories suppose that at sufficiently high energies the strong, electromagnetic, and weak interactions converge to a single fundamental interaction, even though at low energies these interactions appear quite different. Tests of electroweak theory show good agreement between theory and experiment at low energies. Grand unified theories postulate that at extremely high energies the strong interactions can be incorporated into a unified theory. The energy at which this occurs can be estimated from the observed stability of the proton and is believed to be $\gtrsim 10^{15}$ GeV.[5] By general topological arguments[6] such theories necessarily contain stable monopoles with masses on the order of that at which the unification of the strong interactions occurs. Estimates for this range from about 10^{15} to 10^{17} GeV.[4,5]

Grand unified theories when incorporated into big-bang cosmology have had some success in explaining the apparent asymmetry between matter and antimatter in the universe.[7] If the big-bang /unified-theory scenario is correct, monopoles began to appear after the universe cooled to a temperature $kT \sim 10^{15}$ GeV, which happened in about 10^{-35} sec.[3] The resulting number density of monopoles in the universe can be estimated[3,8] with the result that the predicted density is many orders of magnitude larger than number density expected if monopoles dominate the mass of the universe. (See below). Mechanisms for reducing this embarassment of monopoles have been discussed.[3,9] The main point to note here is that theories predict a "large" density of massive monopoles in the universe. Such important objects deserve a serious experimental search effort.

It is therefore appropriate to critically review what limits can be placed on the density and flux of massive monopoles from present data. Despite claims to the contrary (for example in Ref. 3), I find that there are already significant experimental limits on monopole concentration.

ASTROPHYSICAL LIMITS ON MONOPOLE DENSITY AND FLUX IN THE PRESENT UNIVERSE

If we suppose that monopoles with mass $M_M \sim 10^{15}$ GeV/c^2 exist, it is possible to place rather stringent limits on their number density and flux on the basis of general astrophysical arguments.

The most straightforward limit is obtained by supposing that monopoles dominate the mass in the universe. Masses of galaxies can be estimated from the variation of rotational velocity with radius.[10] With this information and galaxy counts it is possible to estimate the average mass density contained in galaxies, $\rho(G)$. It is found that[10]

$$\rho(G)/\rho_C \approx 0.02 , \tag{1}$$

where ρ_c is the critical density which would close the universe if there is no cosmological term. Equation (1) suggests that the universe could contain a more or less uniformly distributed sea of massive monopoles with a mass density as much as $10\rho(G)$ without doing violence to conventional cosmology. This gives an upper limit on the number density of monopoles of

$$n_M \lesssim \frac{10\times(\text{galactic mass})/(\text{monopole mass})}{(\text{distance between galaxies})^3}$$

$$\sim 4\times 10^{-20}\ \text{cm}^{-3} \tag{2}$$

using a typical galactic mass $\sim 10^{11}\ M_\odot$, a mass of 10^{15} GeV/c^2 for the monopoles and $\sim 3\times 10^{24}$ cm between galaxies. If, as is usually assumed, the bulk of the mass of galaxies is in nucleons, the average number density of nucleons in the universe is $\sim 4\times 10^{-6}$ cm^{-3}. Equation (2) then implies

$$n_M/n_N \lesssim 10^{-14} \tag{2'}$$

for the average ratio of monopole to nucleon number density in the universe. As discussed below, the magnetic field of our galaxy or any other they encounter will have accelerated the monopoles to velocities $v \sim 10^{-2}c$. For $n_M \sim 4\times 10^{-20}$ cm^{-3} the flux of magnetic monopoles would be

$$F \approx n_M v \lesssim 3\ \text{monopoles}/(\text{m}^2\text{yr}) . \tag{3}$$

It is possible to obtain much stronger limits for the density of monopoles from arguments based on the energy balance within galaxies. Galaxies are observed to have large-scale magnetic fields ~ 3 μG, in which a monopole with unit magnetic charge would gain energy at a rate ~ 0.1 eV/cm. The total energy gained in the galactic disc will be $\sim 10^{11}$ GeV, so that monopoles with mass 10^{15} to 10^{17} GeV/c^2 would have velocities between 10^{-2} and $10^{-3}c$. The galactic fields are believed to be generated by a dynamo effect due to the nonuniform rotation of ionized gas in the disc.[11] The available power can be estimated. If much of this power goes to accelerate slow monopoles falling into the galactic disc (or generated within the disc), then Parker[11] estimates

$$n_M/n_N \lesssim 10^{-27\pm 1}\left[\frac{\bar{v}}{c}\right]^{-1} , \tag{4}$$

where $\bar{v}$ is the average velocity of the monopoles. The limit above does not necessarily apply to monopoles with $E >> 10^{11}$ GeV which are not significantly deflected by the galactic fields and, on the average, lose almost as much energy as they gain in an encounter with a galaxy. However in the past 10^{10} yr a monopole with $v \sim 10^{-2}c$ will have encountered $<< 1$ galaxy on the average and it is hard to imagine an energy source which would have accelerated them to energies $>> 10^{11}$ GeV. It is therefore unlikely that the total monopole density and flux in the vicinity of earth would exceed Parker's bound by more than an order of magnitude. (It should be noted, however, that this limit does not apply to monopoles that were trapped in matter at an early epoch.)

However, other authors[12] have also estimated the maximum monopole density and flux on the basis of energy balance within galaxies. These tend to be somewhat larger than Parker's limit above. For our purposes it is reasonable to summarize the astrophysical limits as

$$m_M/n_M \lesssim 10^{-22.5\pm 3} \tag{5a}$$

for monopoles with $v \sim 10^{-2}c$. This corresponds to a flux

$$F \lesssim 10^{-8\pm 3}\ \text{monopoles}/(\text{m}^2\text{yr}) . \tag{5b}$$

COULD PREVIOUS SEARCHES HAVE DETECTED MASSIVE MONOPOLES?

Despite the many searches for monopoles, it is fair to ask whether there are *any* direct experimental limits on monopoles. Preskill[3] and Glashow[13] have argued that all previous monopole searches would have been insensitive to very massive monopoles. In brief, all of the experiments suffer from one or more of the following deficiencies:

(1) The searches for monopoles at high-energy accelerators were hopelessly below the threshold for their production.

(2) Searches for monopoles in cosmic rays looked for particles with extremely high ionization, as expected for a highly relativistic monopole. However the monopoles of grand unified theories are so massive it is unlikely they will be traveling with velocity sufficient to ionize heavily.

(3) Searches for massive monopoles trapped in matter would fail because the earth's gravity exerts a force much larger than any force that binds them in the sample so that any monopoles would be extracted.

Though the first point above is certainly true, I shall argue that points (2) and (3) are only partially correct and that, in fact, significant experimental limits on massive primordial monopoles can be arrived at from existing data.

ENERGY-LOSS MECHANISMS FOR MASSIVE MONOPOLES

If, as discussed above, monopoles are accelerated to energies $\sim 10^{11}$ GeV by galactic magnetic fields, the monopoles can be expected to have extraordinarily large ranges in matter. Despite their high energies, such monopoles cannot undergo inelastic collisions with nucleons because the available energy in the monopole-nucleon center-of-mass system is $<< 1$ MeV, which is well below the threshold for pion production. Furthermore the mass of the monopoles is $\sim 10^{14}$ times that of a typical atom so that even the accretion of a large number of atoms by the monopole would not slow it appreciably. The energy-loss mechanisms that can be expected to be significant are as follows.

(1) Ionization. Monopoles with sufficient velocity lose energy by ionizing atoms in the medium. Typical ionization energies are ~ 10 eV. The maximum energy a massive particle with velocity v can impart to a free electron is $\approx 2m_e v^2$. This suggests a "threshold" for significant ionization given by

$$2m_e v^2 \gtrsim 10 \text{ eV} . \tag{6}$$

This implies $v \gtrsim 3\times 10^{-3}c$ as the effective threshold. As discussed above monopoles of mass 10^{15} to 10^{17} GeV/c^2 will have typical velocities $\sim 10^{-2}c$ to $10^{-3}c$ as a result of acceleration in the magnetic field of our galaxy. There appears to be no reliable calculation of ionization losses for slow monopoles. However, it is expected that the energy loss for magnetic charges will grow faster above threshold than that for electric charges because the expression for the latter contains an explicit v^{-1} dependence which does not appear for monopoles. Thus it seems likely that a reasonable fraction of the monopoles will ionize sufficiently to be detected in scintillation counters and proportional chambers. Ullman[14] and others have argued that even monopoles with $v << 10^{-3}c$ will ionize appreciably. This is a very important practical question in searching for massive monopoles; a complete analysis of this problem is overdue.

(2) Eddy-current losses. The long-range magnetic field of a moving monopole causes eddy currents in a conducting medium through which it passes. The resulting energy loss has been estimated by Martem'yanov and Khakimov.[15] Using their Eq. (1), I find for aluminum

$$\left[\frac{dE}{dx}\right]_{\mathrm{EC}} \approx 140\frac{v}{c} \text{ GeV/cm} . \tag{7}$$

For a monopole with $v \approx 10^{-2}c$ and $M \approx 10^{15}$ GeV/c^2 the range in aluminum will be $\sim 10^{11}$ cm or about 100 times the diameter of the Earth.

(3) Hysteresis losses in ferromagnetic media. These are always quite small. For very slow monopoles in iron, I estimate[16]

$$\left[\frac{dE}{dx}\right]_{\mathrm{HYS}} \sim 0.1 \text{ MeV/cm} . \tag{8}$$

EXPERIMENTAL LIMITS FOR MONOPOLE FLUXES

Essentially all of the experiments explicitly undertaken to search for monopoles in cosmic rays would not have been sensitive to monopoles with masses $\gtrsim 10^{15}$ GeV/c^2 and velocities $\lesssim 10^{-2}c$. In these experiments it was generally assumed that the monopoles would show the very heavy ionization characteristic of a relativistic monopole. However, as discussed above, the monopoles of grand unified theories are likely to be traveling at velocities such that the ionization will be small, perhaps negligible. The typical kinetic energies of the monopoles are expected to be $\sim 10^{11}$ GeV. If the mass of the monopoles is $< 10^{17}$ GeV/c^2 their typical velocities will be $\gtrsim 10^{-3}c$. The energy spectrum of the monopoles will be quite broad. It seems reasonable to expect that a large fraction of the monopoles *will* produce significant ionization in detectors if $M < 10^{17}$ GeV/c^2. The ionization is a very strong function of velocity just above threshold[15] so the monopoles will appear as particles with highly variable ionization density.

A convenient unit for comparing the ionization of different particles is that of a so-called minimum-ionizing particle. This is roughly the ionization produced by a relativistic single charged particle, or approximately that of a cosmic-ray muon in the detector. Numerous experiments have been undertaken to search for fractionally charged particles or "quarks" in cosmic rays.[17] These would appear as particles with ionization between 0.1 and 0.5 minimum depending on whether the charge is $\frac{1}{3}e$ or $\frac{2}{3}e$. No generally accepted candidates for fractionally charged particles have been discovered in cosmic rays. These experiments can also be interpreted as unsuccessful searches for lightly ionizing massive monopoles. Limits on fluxes of quarks or lightly ionizing monopoles from these experiments are[17]

$$F \lesssim 300 \text{ monopoles}/(\text{m}^2\text{yr}^1) . \tag{9a}$$

Ullman[14] gives a limit

$$F \lesssim 100 \text{ m}^{-2}\text{yr}^{-1} \tag{9b}$$

for particles with $\beta < 10^{-3}$ which produce an ionization greater than $2.5\times$minimum. Better limits exist for very heavily ionizing monopoles; the best seems to be that of Kinoshita and Price[18] who give a limit

$$F \lesssim 0.4 \text{ monopoles}/(\text{m}^2\text{yr}) . \tag{9c}$$

The authors estimate that their search would have been sensitive to monopoles with velocity $\gtrsim 0.02c$. The experimental limits (9) on the flux of monopoles are considerably weaker than the indirect astrophysical limit (5b). It should also be emphasized that if, as discussed above, monopoles have typical energies $\sim 10^{11}$ GeV as a result of the acceleration in galactic magnetic fields, the limit (9c) would only apply to monopoles with $M \lesssim 5\times 10^{14}$ GeV/c^2, the limit (9b) would apply to $M \sim 10^{18}$ GeV/c^2, and limit (9a) for $M \lesssim 10^{16}$ GeV/c^2, these mass limits, however, depend to a large extent on assumptions about the ionization produced by slow monopoles.

EXPERIMENTAL LIMITS ON MONOPOLE CONCENTRATIONS IN MATTER

The most sensitive direct searches for monopoles, primordial or otherwise, trapped in matter are those of Eberhard *et al.*[19] These experimenters searched for monopoles in a variety of terrestrial material, in meteorites, and in lunar soil samples. The details of the experiment need not be described here. All that matters is that these experiments should have been sensitive to the presence of even one monopole in any of the samples provided that the pole strength was comparable to or greater than the minimum value derived by Dirac.[1] No monopoles were found.

The limits on monopole concentration from these experiments are impressive, but before accepting their significance we must first ask whether any monopoles in the samples would have been extracted by Earth's gravity. A monopole with a weight $\sim 10^{14}$ that of a typical atom would have to be bound to a macroscopic portion of the sample by a long-range force to avoid being extracted. Such a force would in fact appear if a monopole tries to leave a ferromagnetic or paramagnetic material. The monopole because of its magnetic field feels an attractive image force, similar to that which is felt by an electric charge as it leaves a conductor. The image force on a monopole is a classical effect due to its long-range magnetic field, and a lower bound on its magnitude can be estimated reliably. Goto, Kolm, and Ford[20] estimate that for a pole of unit strength near iron the image force is

$$F_{\text{image}} \approx 10 \text{ eV}/\text{Å} \tag{10}$$

and the depth of the potential well is approximately 740 eV. For magnetite (Fe_3O_4) the force and well depth are about one-third those for iron.

In the same units, the weight of a monopole of mass 10^{15} GeV/c^2 is approximately 10^{-2} eV/Å. Therefore once trapped, monopoles of mass $\lesssim 10^{18}$ GeV/c^2 will remain in the samples *unless* they have undergone large accelerations or have been heated above the Curie point.

Thus the ferromagnetic samples studied by Eberhard *et al.* seem to be reasonable places to look for massive monopoles. Nevertheless the terrestrial samples and, to a lesser extent, the lunar samples they used do not appear to be good prospects for the following reasons.

(1) If the iron in the samples ever became nonferromagnetic—either because it was heated

above the Curie point or it reacted chemically—the monopoles would be lost. The temperatures of the earth and moon were probably well above the Curie point after they condensed from the solar nebula. Most ferromagnetic material now near the earth's surface has been heated or oxidized at least once since then. Thus any monopoles trapped in the primordial material would now be at or near the center of the earth (or moon).

(2) Monopoles would be very unlikely to be stopped in a sample of material on the earth's or moon's surface. For example, a monopole striking the earth must arrive with a velocity equal to or greater than the escape velocity, $\approx 10^4$ m/s. With reasonable estimates of the conductivity of the earth's core, it would take $\gtrsim 10^6$ transits through the earth to stop a monopole with this initial velocity. To be trapped in a ferromagnetic specimen, the monopole would have to stop within approximately 10^{-3} cm of the lower surface. Otherwise it will acquire enough kinetic energy to break out of the image potential well as it falls back through the lower surface. In other words the effective thickness of any sample, no matter how large the actual thickness, is $\sim 10^{-3}$ cm.

The first objection above does not necessarily apply to the meteorite samples studied by Eberhard *et al.* Meteorites are generally believed to be fragments of asteroids (or possibly comets) which condensed out of the solar nebula about the same time the earth and planets formed.[21-23] As I discuss in more detail below, the interiors of asteroids—or meteorites—would seem to be good places to look for trapped primordial monopoles.

Most meteorites fall into one of two broad classes: iron meteorites which are mostly iron with a few percent of nickel and $< 1\%$ of other elements, and stony meteorites or chondrites which typically contain $\approx 5\%$ by weight of metallic iron in the form of millimeter-sized grains. The stony ones were never remelted after they were accreted in the parent body $\sim 5\times 10^9$ yr ago. From the crystalline structure of the iron meteorites their cooling rates can be estimated and these are suggestive of cooling within a body ~ 10 km in radius.[21,22] The number of parent bodies is believed to be ~ 10.[21] The iron meteors probably came from raisinlike bodies embedded in a stony matrix in the parent.

The iron grains in stony meteorites seem to be nearly ideal monopole traps. Once trapped in a grain by the image force the monopoles are isolated and unlikely to undergo annihilation with an antipole. They are also protected against ablation and heating as the meteorite descends through the earth's atmosphere. Similar considerations apply to iron meteorites which generally consist of bands or lamellae of ferromagnetic kamacite (94% Fe + $\approx 6\%$ Ni) 0.1 to 10 mm thick, alternating with nonmagnetic taenite.[22,23] Inclusions of other nonferromagnetic minerals are also very common. Thus in the iron meteorites as well the monopoles will be trapped at these boundaries where they are isolated and protected.

Eberhard *et al.*[19] studied samples of both stony meteorites (fragments of the Allende and Tulia) and iron ones (the Odessa and Nordheim). The total weight of the samples was ≈ 2 kg. We suppose for the moment that any monopoles survived the fall and ask what limits can be placed on monopole concentration from these samples. The iron would contain all the monopoles which condensed with the original material. If there is < 1 monopole in 2 kg of material the number of monopoles per nucleon is

$$\frac{n_M}{n_N} \lesssim \frac{1 \text{ monopole}}{(2000\text{ g})\times 6\times 10^{23}\text{nucleons/g}} \cong 10^{-27}\frac{\text{monopoles}}{\text{nucleon}} . \qquad (11)$$

This is about 4 orders of magnitude smaller than the astrophysical bound, Eq. (5a).

Whether the monopoles remain in the meteorite during its fall to earth is determined by the maximum deceleration the meteorite undergoes and the monopole mass. Monopoles of sufficiently small mass will surely survive. The problem is to estimate the upper limit for the mass of surviving monopoles. Meteoritic iron (kamacite) is typically 6% nickel with few other impurities. The saturation magnetization is about half that of iron.[23] Following Goto *et al.*[20] the maximum image force will be ≈ 5 eV/Å for a monopole trying to leave the kamacite.

The maximum deceleration of a meteorite in the earth's atmosphere ranges from 90g to 1000g, depending on the angle of incidence.[22] The inside of the meteorite remains cool.[23] The maximum deceleration on impact with the ground varies enormously with the size of the fragment and the surface it falls onto. Small fragments of the Allende meteorite were recovered with delicate surface features still intact. Others have been found on top of thin ice[22] or embedded < 1 m in deep snow.[24] Large stony meteorites almost always break up in the atmosphere. Impact velocities of the fragments are estimated to be 10–20 m/s.[25] Most iron meteorites reach a terminal velocity which is <200 m/s well before they hit the ground.[23]

It seems reasonable to assume that the typical maximum accelerations the meteorites were exposed to was $\sim 1000g$ in order to estimate the maximum mass for which the limit in Eq. (11) applies. Containment then requires

$$1000Mg \lesssim 5 \text{ eV/Å}$$

or (12)

$$M \lesssim 5\times 10^{14} \text{ GeV}/c^2 .$$

Thus the range of monopole masses to which the present meteorite samples would be sensitive overlaps the mass range expected in grand unified theories. The range of sensitivity could easily be extended upward by about an order of magnitude by choosing meteorites more carefully.[26] The Antarctic meteorites[27] which presumably fell in deep snow are good candidates. At least some of these must have experienced decelerations $\lesssim 100g$ in the atmosphere and comparable or smaller decelerations on impact.

The above mass limitation can be removed entirely if meteoroids (or samples from asteroids or comets) are retrieved and tested for monopoles in space.[28] This should be possible within the next decade or so.[29]

Though the experimental limits for trapped monopoles are already impressive,[30] more sensitive searches for monopoles in flight should also be undertaken. There is always the possibility that primordial magnetic fields may have accelerated essentially all the monopoles to high energies well before the formation of the solar system, so that very few became trapped in matter. There is also the possibility that most of any monopoles trapped in the parent asteroids, or the infalling material which formed them, annihilated with antimonopoles before the material cooled below the Curie point and the ferromagnetic traps formed. (However this seems unlikely because in the weak gravitational field of an asteroid even the image force due to *paramagnetism* should be sufficient to trap the monopoles at grain boundaries and prevent their annihilation. Also even a small external magnetic field will tend to keep poles and antipoles apart and minimize the chance of annihilations.)

CONCLUSIONS

Direct experimental searches for massive monopoles in flight provide limits on the flux of massive monopoles of $\lesssim 300 \text{ m}^{-2}\text{ yr}^{-1}$ for $\beta \gtrsim 5\times 10^{-3}$ and $\lesssim 0.4 \text{ m}^{-2}\text{ yr}^{-1}$ for $\beta \gtrsim 2\times 10^{-2}$. Astrophysical arguments based on the existence and energy sources of the large-scale magnetic fields within galaxies suggest limits for the flux $F \lesssim 10^{-8\pm 3} \text{ m}^{-2}\text{ yr}^{-1}$ and concentration $\lesssim 10^{22.5\pm 3}$ monopoles per nucleon. Monopoles of mass $\sim 10^{15}$ GeV/c^2 would be expected to have velocities $\beta \sim 10^{-2}$ as a result of acceleration by these magnetic fields.

Previous experimental searches for trapped monopoles in meteorite samples[19] yield much better limits for monopoles with masses $\lesssim 5\times 10^{14}$ GeV/c^2. From these searches the limit of monopole concentration is $\lesssim 10^{-27}$ monopoles/nucleon. This is some 27 orders of magnitude smaller than the concentration expected in a big-bang cosmology if monopoles are produced in a second-order phase transition[3,8] and most of the monopoles survive to the present epoch.[31] This limit is comparable to the monopole density predicted in more recent calculations which assume a first-order transition[9] produces the monopoles.

The mass limit from meteorite searches can easily be raised by looking at carefully selected meteorites and eventually by retrieving meteoroids from space. The concentration limit can of course be improved by looking at larger samples.

To improve the limits on monopoles in flight significantly, very large detectors will be required. This type of experiment should be regarded as complementary to searches for trapped monopoles.

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[26] Care should also be exercised in handling meteorites to be searched for monopoles. Monopoles could be dislodged if the samples are suddenly turned upside down. The potential well due to the image force is only ≈ 400 eV deep (Ref. 19). A monopole gains enough kinetic energy to break out of the well if it falls a distance $\gtrsim 0.1$ mm. (The distance depends critically on the mass of the monopole, hysteresis losses [Eq. (8)], and the detailed motion of the sample.) This should be less of a problem with stony meteorites because of the small size of the iron grains. Retrieving meteors in space and testing them for monopoles there would eliminate this problem.

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[28] Meteorites could, of course, contain monopoles that stopped in the parent asteroid (or the meteoroid itself) after the solar system formed. However the monopoles would have to have very low energies to stop in the material. This seems unlikely in view of the magnetic field in our galaxy.

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[30] R. Carrigan [Nature 288, 348 (1980)] gives an interesting indirect limit on monopole concentration in the Earth, $n_M/n_N \lesssim 10^{-28}$. This is based on the assumption that monopoles accreted with the material that formed the Earth and are now trapped in its core. He suggest that each time the Earth's magnetic field reverses direction some of the monopoles and antimonopoles annihilate as they pass each other near the Earth's center. He estimates that this source could account for up to 25% of the Earth's heat; from this he arrives at an upper limit on monopole concentration.

[31] Preskill[3] and Einhorn *et al.*[8] estimate a density of monopoles $\sim 10^{-6}T^3$ to $10^{-10}T^3$ was produced in the big bang. In the present universe with $T \approx 2.7\,^{\circ}\mathrm{K}$ this translates to an average monopole density $\sim 10^{-5}$ monopoles/cm^3. This, of course, is many orders of magnitude greater than even the astrophysical limit.[2] Preskill argues that the rapid expansion of the universe after the big bang will prevent the complete annihilation of the monopoles.