Is there a local source of magnetic monopoles?

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Cabrera\(^1\) has reported the possible detection of a magnetic monopole in flight with magnetic charge \(g\) given by the Dirac condition\(^2\) \(2eg = \hbar c\). Here, we accept the Cabrera candidate as a 't Hooft–Polyakov\(^3,4\) monopole of mass \(M \approx 10^{15}\) GeV as expected\(^5\) in \(SU(5)\) or other grand unified theories. The monopole flux on Earth, on the basis of the single candidate, is \(f \approx (0.1)\) cm\(^{-2}\) yr\(^{-1}\) (2\(\pi\)sr)\(^{-1}\), presumably consisting of roughly equal numbers of north and south monopoles. Galactic or intergalactic monopoles will have typical velocities of \(~300\) km s\(^{-1}\). The Cabrera flux would correspond to a mass density \(f M / \nu \approx 1\) GeV cm\(^{-2}\). Because the mean mass density of the Universe cannot exceed \(10^{-6}\) GeV cm\(^{-3}\), the mean flux of monopoles in the Universe must be at least five orders of magnitude smaller than \(f\) (refs 6,7). This would not be a problem if the monopoles were concentrated in the Galaxy. However, Parker has shown\(^6\) that the existence of galactic magnetic fields is inconsistent with a mean galactic monopole flux of \(10^{-7}\) cm\(^{-2}\) yr\(^{-1}\). It follows that \(f\) must be a local flux resulting from the special nature of the observation site. Three possibilities come to mind: the local monopole flux may be associated with the Earth, the Sun, or with the Solar System as a whole.

If the monopoles observed at the Earth's surface originate from the core, as does the local magnetic field, and if the flux is not time dependent, the Earth has emitted more than \(10^{2}\) monopoles since its birth, implying an initial (or present) monopole density \(n \approx 1\) cm\(^{-3}\). However, the density of monopoles in the Earth’s core is bounded by

\[
 n < B/8\pi\mu_0
\]  

where \(\tau = 10^4\) yr is the characteristic growth time of the geomagnetic field, \(v\) is the monopole velocity within the core, and \(E\) is the magnetic field within the core. With a core field \(\sim 100\) G, we expect \(v \sim 3\) km s\(^{-1}\) on the basis of either magnetic or gravitational force arguments. This gives a limit \(n < 10^{-9}\) cm\(^{-3}\). Thus, the Cabrera flux cannot originate from the Earth.

Can the monopole flux seen on Earth originate from the Sun, in the fashion of radiative energy or solar wind? If so, the Sun has emitted (and presumably still contains) some \(10^{36}\) monopoles. This implies a mean solar monopole density \(n \approx 10^{3}\) monopoles cm\(^{-3}\), with \(10^{-5}\) of the solar mass made up of monopoles. If the monopoles are gravitationally bound to the Sun, they must have velocities \(\sim 400\) km s\(^{-1}\) and kinetic energies \(\sim 10^{10}\) GeV. They will lose energy in nuclear collisions, and by inducing currents in the highly conductive solar medium. The energy they dissipate by these losses must be compensated by magnetic acceleration. Thus, there must be a mean interior magnetic field in the Sun of \(\sim 10^{2}\) G so that

\[
g(B) \sim \frac{dE}{dz} \sim 10\text{ MeV cm}^{-1}
\]  

The characteristic time of the solar interior field is assumed to be \(\sim 20\) yr, the period of the sunspot cycle. With these values of \(B\) and \(\tau\), equation (1) yields an upper bound on the density of monopoles in the Sun, \(n < 10^{-7}\) cm\(^{-3}\). Moreover, the ohmic loss due to \(10^{36}\) orbiting monopoles is \(\sim 10^6\) \(\pi\). For both these reasons, it is difficult to explain the observed monopole flux in terms of a direct solar flux. Of course, it could be that most of the solar monopoles are concentrated in the centre of the Sun, and are only rarely extricated by transient magnetic fields. Escape velocity for these monopoles is \(\sim 1,400\) km s\(^{-1}\), which would require magnetic fields \(\sim 10^7\) G over distances \(\sim R_{\odot}\).

Can the local monopole flux result from a diffuse cloud of monopoles which are in newtonian orbits about the Sun, rather

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like meteorites and meteoric dust? Their velocities about the Sun will then be ~30 km s⁻¹, while their arrival velocities at Earth will vary from 10 to 70 km s⁻¹ as do the arrival velocities of meteorites. Their density must be ~10⁻¹⁵ cm⁻³ to explain the observed flux, corresponding to ~10¹⁴ monopoles within the Earth's orbit. These monopoles are subject to a solar magnetic field ~3 × 10⁻⁹ G, and a consequent magnetic force which is ~10⁻¹⁹ of the solar gravitational force. Following Parker², we have estimated the time over which the magnetic perturbation significantly alters the energy of a monopole in solar orbit. We assume that the distant solar magnetic field fluctuates over a time scale of half a solar rotation period, T = 10⁶ s, and that its magnitude at 1 AU is ~3 × 10⁻⁹ G. The residence time of a monopole in solar orbit is given by

\[ t = \left(\frac{\nu}{c}\right)^2 T^{-1} \omega^{-2} \quad (3) \]

where \( \omega = gB/Mc \approx 2 \times 10^{-15} \) Hz. We find \( t \approx 100 \) Myr. The eventual fate of the orbiting monopoles will be to fall into the Sun, or to escape the Solar System. In any case, to maintain the local monopole flux, a source of ~10⁹ monopoles per second is required.

We must verify that the monopole flux on the Earth does not generate too great a monopole density within the Earth. The incident monopoles have kinetic energy ~10³ GeV and lose ~1 MeV cm⁻³ (hence ~10⁻³ GeV) as they traverse Earth. They pass through the Earth without stopping. Their density, \( n = \frac{10^{-15}}{c} \text{ cm}^{-3} \), is well within the bound set by equation (1).

The monopole cloud of the Solar System is maintained either by an external (cosmic) or internal (solar) flux. Cosmic monopoles traversing the Sun may lose enough energy by ohmic losses or magnetic deceleration to be captured into solar orbit. Indeed, ~10⁹ monopoles per second pass through a hypothetical sphere of solar radius if the Parker bound on the flux of galactic monopoles is saturated. The actual number impacting the Sun is larger by the factor \( 1 + (v_B/v) \) where \( v_B \) is the monopole velocity and \( v_B = 600 \text{ km s}^{-1} \) is the escape velocity from the Sun. As \( (v) \approx 300 \text{ km s}^{-1} \), the enhancement is considerable, particularly for slower monopoles. The Sun may well capture enough monopoles to sustain its cloud.

On the other hand, the cloud may be fed internally by a flux of ~10⁹ monopoles per second which is extracted from the Sun by solar flares. Either mechanism implies a solar monopole number of ~10³⁰⁶ and a density of \( n = \frac{10^{-15}}{c} \text{ cm}^{-3} \), corresponding to an acceptable ohmic dissipation of ~10⁻²⁷ L⊙. With kilogauss mean fields, equation (2) is satisfied. The limit on monopole density given by equation (1) is just saturated, a result whose significance we discuss below.

Simple considerations of magnetic diffusivity yield the expression \( \dot{T} = (4\pi n \gamma c^3) R^2 \) for the characteristic time of the solar magnetic field. This is known to overestimate \( \dot{T} \) by six orders of magnitude⁸. In the presence of monopoles, \( \dot{T} \) is correctly determined to be ~20 yr by the magnetic dissipation time given in equation (1).

Monopoles within the Sun can have other significant effects. They can lead to a lower central temperature by promoting heat transfer from the solar interior, or by catalyzing nuclear fusion or nucleon decay. This could ameliorate the solar neutrino problem.

It is suggested that magnetic monopoles may have a substantial cross-section \( \sigma \) to induce nucleon-number violating processes such as

\[ \text{Monopole} + p \rightarrow \text{Monopole} + (e^- \text{ or } \pi^-). \quad (4) \]

This process can be observed directly as monopoles pass through material on Earth; it can contribute to energy production in the Sun; and it can act as a source of high-energy solar antineutrinos which can be detected on Earth. Monopole-induced nucleon decay, seen in the laboratory, will not seem to conserve momentum because the recoiling monopole is not detected. A limit can be placed on \( \sigma \) from known limits on the nucleon lifetime: \( \sigma L < \tau_{\pi}^{-1} \) where \( \tau_{\pi} \) is the lower limit on the proton lifetime in experiments where momentum conservation is not imposed. Taking \( \tau_{\pi} > 10^{31} \text{ yr} \), we obtain \( \sigma < 10^{-28} \text{ cm}^{2} \).

With this cross-section, catalytic nucleon decay within the Sun cannot account for no more than ~10⁻⁶ L⊙. However, this process can also yield GeV electron antineutrinos, with a flux on Earth as high as ~10⁻⁵ cm⁻² s⁻¹. A search for this kind of solar emission is called for.

The net flux of monopoles from all stars in the Galaxy would amount to ~10¹⁰ monopoles per year. These will be accelerated by galactic magnetic fields to an escape energy of ~10³ GeV requiring an energy source of ~10⁻¹⁴ L⊙. This is easily compatible with the estimated energy content of the galactic magnetic field \( (B^2/8\pi)V \approx 10^{-7} \text{ GeV} \) and a rest time of one galactic period, or ~10³ yr.

We conclude that the Cabrera flux of magnetic monopole can be understood in terms of an orbiting cloud of monopole in the Solar System, which is replenished by a small 'monopole wind' from the Sun or from the Galaxy. Monopoles may have an important role in solar energetics. Our hypothesis can be established if the monopole flux on Earth is shown to be similar (in velocity distribution, angular distribution, and its seasonal and diurnal variations) to the observed flux of meteorites, except for the fact that monopoles (but not meteorites) pass freely through the Earth.

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