SLAC-PUB-2977
September 1982
(E/T)

NEW LIMITS ON A GALACTIC MONOPOLE FLUX*

D. M. Ritson
Stanford Linear Accelerator Center, Stanford University
Stanford, California 94305

Abstract

It is shown that stars must stop and trap a substantial fraction of any incident galactic monopole flux, provided their masses are not too large. The trapped monopoles will act to "short-out" the magnetic fields of stars. The apparent persistence over long time periods of large and coherent magnetic fields in the peculiar A stars is used to set a bound on the trapped density of monopoles in these stars. The inferred limit on the flux of monopoles, incident on these stars, is substantially lower than the present Parker bound.

A recent publication by B. Cabrera[1] has resulted in a renewed interest in the limits on monopole fluxes that can be set by astrophysical data. Bounds have been set from the persistence times of galactic magnetic fields by Turner, Parker, and Bogdan[2] using the assumption that galactic fields have lifetimes in excess of 10^8 yrs. These considerations limit the flux of monopoles in the galaxy to $< 3\cdot10^{-8}$ /cm^2/yr/ster. It has been argued that a substantial fraction of the monopole flux impinging on the sun would be captured and later find its way into solar orbits.[3] This flux of monopoles would then be expected to reside in the solar system for $\sim10^8$ yrs and could result in an enhanced flux of monopoles in the solar system of 10^6 times the present Parker bound, sufficient to account for the Cabrera observation. Below we derive a substantially stronger bound to the possible flux of monopoles with a monopole mass $< 5\cdot10^{16}$ GeV.

Coherent magnetic fields of 200 to 34,000 gauss are observed in slowly rotating peculiar A stars.[4] The magnetic field strengths are anticorrelated with the rotational velocities of these stars[5] and for this reason their presence is usually attributed, not to dynamo effects (mechanical energy transformed to electric energy), but to the survival of "fossil" fields frozen into the structure during the process of stellar formation.[6] If these fields have indeed persisted for 10^6–10^9 yrs, stringent upper bounds on the flux of galactic monopoles can be set. The galactic

(Submitted to Publications)

---

*Work supported by the Department of Energy, contract DE-AC03-76SF00515.

monopole flux is assumed to be gravitationally bound to the galaxy and hence to have $\langle \beta \rangle \sim 10^{-3}$. While controversy exists as to the exact energy loss expected for slow monopoles moving in atomic systems, the derivation of losses in a classical non-degenerate electron gas (hot plasma) is straightforward. The magnitude of these losses is such that a substantial fraction of the galactic monopole flux impinging on a typical star should stop within the star. Subsequently these monopoles will drift around in the interior under the combined influence of gravity and the magnetic field forces. As we shall show "ionization-losses" act to provide strong viscous damping of the motion and drift velocities are low, even in the presence of strong magnetic fields. For magnetic forces strong compared to the gravitational forces, computer modeling of the motions shows that the monopoles will be trapped into orbits circling the current sources. For magnetic forces weak compared with the gravitational attraction the monopoles will drift into a central stable trapping point and will not circulate around the current sources. An intermediate regime exists in which a fraction of the monopoles is trapped at a central point and a fraction are trapped in circulating orbits. Substantial trapping into circulating orbits exists for magnetic fields > 10,000 Gauss and monopole mass $< 5\cdot10^{16}$ GeV. Thus when magnetic forces are strong compared to the gravitational forces monopoles steadily accumulate into circulating orbits within the stellar interiors. These circulating monopoles remove energy from the magnetic fields and result in finite and calculable lifetimes of the magnetic fields.Thus persistence of a magnetic field over a long period of time permits a bound to be set on the accumulated density and incident flux of monopoles. This bound turns out to be independent of the magnetic field-strength and depends only on the lifetime, radius and mass of the star. The flux limit is substantially lower than the Parker bound, and even with the most optimistic enhancement assumptions is inconsistent with the the Cabrera "flux". Details of the above arguments follow.

Energy Loss Relations for Monopoles in Hot Classical Plasma

We consider only cases for which both the the monopole and the electron velocities are non-relativistic. Additionally we assume that the electron gas in the hot plasma is non-degenerate. Our notation follows standard conventions

g	is the charge on the monopole (assumed to be $e/2\alpha c$).
N_e	is the number of electrons per cm^3.
$v_e(\beta_e)$	is the mean electron velocity.
$v_{mp}(\beta_{mp})$	is the monopole velocity.
r_e	is the classical radius of the electron.
α	is the fine structure constant.
r_{pl}	is the plasma screening radius $1/\sqrt{(4r_eN_e)}$.
m_e	is the electron mass in units of energy.
m_{mp}	is the monopole mass in units of energy.
R_0	is the radius of the star.

To facilitate numerical estimations, we will approximate interior stellar conditions as a density of $N_e \sim 9\cdot10^{23}$ electrons cm^{-3} and a temperature of one million degrees Kelvin corresponding to a mean β_e of $2.2\cdot10^{-2}$. Subsequently these are referred to as "standard" conditions for stellar interiors.

<u>Case</u> <u>A</u>: $v_{mp} > v_e$.

The result for this case has been approximately derived previously[7] and is

$$dE/dx = -4\pi N_e r_e^2 m_e (gc/e)^2 \ln(\alpha\pi r_{pl}/r_e). \qquad (1)$$

Writing this in terms of S_0, the "stopping-power"

$$dE/dx = -S_0 \qquad (2)$$

S_0 for standard stellar conditions is ~ 6.1 GeV cm^{-1}.

<u>Case</u> <u>B</u>: $v_{mp} < v_e$.

As the velocities of the monopoles are expected to be in the range of 10^{-3}c to 10^{-5}c this will be the case of practical interest. The derivation of the energy loss formula leads to the result[8]

$$dE/dx = -S_0 . v_{mp}/v_e \ (=-6.1 \cdot v_{mp}/v_e \text{ GeV cm}^{-1}) \qquad (3)$$

The only difference from the previous case is the inclusion of the velocity dependent factor v_{mp}/v_e.

Integrating equation (3) we obtain the equation relating the path length traversed X_0 to the change in β_{mp}, $\Delta\beta_{mp}$

$$X_0 = \beta_e \Delta\beta_{mp} m_{mp}/S_0 \qquad (4)$$

and for standard conditions

$$X_0 = 3.3 \cdot 10^{-3} \Delta\beta_{mp} m_{mp} [\text{GeV}] \text{ cm}. \qquad (5)$$

Using a typical path length in an A_p star of ~$2 \cdot 10^{11}$ cm and a monopole mass of ~$5 \cdot 10^{16}$ GeV the β will decrease by ~10^{-3} per traversal leading to substantial capture probability. We therefore approximate ϵ, the capture probability, as:

$$\epsilon = 1 \text{ for } m_{mp} < 5 \cdot 10^{16} \text{ GeV}. \qquad (6)$$

Monopoles in the interior of stars will drift under the influence of magnetic fields with a terminal drift velocity v_{dr} (β_{dr}) set by the relation

$$Bg = dE/dx = S_0 \beta_{dr}/\beta_e \quad \text{or} \quad \beta_{dr} = Bg\beta_e/S_0. \qquad (7)$$

Using standard conditions we obtain the result

$$\beta_{dr} = 1.5 \cdot 10^{-8} B[\text{Gauss}]. \qquad (8)$$

Even for fields as high as several tens of thousands of Gauss this results in β_{dr} being smaller than the escape velocities of ~$2 \cdot 10^{-3}$ required to leave the surfaces of stars.

Lifetimes of Stellar Fields and Flux Limits

The average density of monopoles in a star ρ_{mp}, is given in terms of the stellar lifetime τ, the incident flux of monopoles, F_{mp}, and the capture probability, ϵ, by

$$(4/3)\pi R_0{}^3\rho_{mp} = 2\pi^2 R_0{}^2 \epsilon F_{mp}\tau \qquad (9)$$

and the lifetime τ' of the magnetic field B is given by[9]

$$\tau' < B/8\pi\rho_{mp} g v_{dr}. \qquad (10)$$

Substituting B_{dr} from equation (7) into equation (10)

$$\tau' < S_0/8\pi\rho_{mp} g^2 c B_e. \qquad (11)$$

Assuming that the lifetime of the magnetic field τ' is commensurate or longer than the lifetime of a typical A_p star $\sim 5\cdot 10^8$ yr, combining equations (9) and (11) and substituting the numerical values for a standard stellar interior, we obtain numerical limits on ρ_{mp} and F_{mp} of

$$\rho_{mp} < 6.9\cdot 10^{-14}\ \mathrm{cm}^{-3}. \qquad (12)$$

$$\epsilon F_{mp} < 2\cdot 10^{-12}/\mathrm{cm}^2/\mathrm{yr/ster}. \qquad (13)$$

Using the approximation $\epsilon = 1$

$$F_{mp} < 2\cdot 10^{-12}/\mathrm{cm}^2/\mathrm{yr/ster}\ \text{for}\ m_{mp} < 5\cdot 10^{16}\ \mathrm{GeV}. \qquad (14)$$

If there is an enhancement factor, η, due to capture into solar orbits as suggested by Dimopolous et al.,[3] the monopole flux experimentally observed at the earth, F_{exp}, should be

$$F_{exp} < 2\cdot 10^{-12}\eta/\mathrm{cm}^2/\mathrm{yr/ster}. \qquad (15)$$

Conclusions

Under the assumption that the magnetic fields of A_p stars are fossil fields that have survived over the lifetime of the star, a very stringent limit can be set on the flux of galactic monopoles with mass less than $5\cdot 10^{16}$ GeV. This flux is sufficiently small that detection is unlikely by any methods suggested to date. Enhancement by the mechanism suggested by Dimopolous et al.[3] is a possibility. However such a mechanism requires either energy losses in passage through the sun of the right order of magnitude to result in efficient capture into solar orbits, or relatively efficient mechanisms for reemission of the monopoles stopped in the sun. Even combined with the most optimistic enhancement factor[3] $\eta \sim 10^6$, the above bound would limit the flux observed at the earth to less than $2\cdot 10^{-6}$ /cm²/yr/ster, substantially less than the flux of approximately 10^{-2} /cm²/yr/ster suggested by the Cabrera observation. Therefore if a monopole flux should be confirmed, it would imply either that the monopole mass $> 5\cdot 10^{16}$ GeV, or that fields in magnetic stars are established in times $< 10^{-4}$ yr.

Acknowledgements.

I am particularly indebted to D. Groom for careful reading and criticisms of the above paper. I have benefited considerably from discussions with B. Cabrera, R. Wagoner, and E. N. Parker.

References.

1. B. Cabrera, Phys. Rev. Lett. 48, 1378 (1982).
2. M. S. Turner, E. N. Parker, and J. J. Bogdan, EF1-82-18 Chicago.
3. S. Dimopolous, S. L. Glashow, E. M. Purcell, F. Wilczek, NSF-ITP-82-62. This paper is in error by a large factor on the dE/dx losses of monopoles. However the basic conclusion of this paper that substantial enhancements might be possible is not substantially changed.
4. G. W. Preston, Ap. J. 164, 309, (1971).
5. J .D. Landstreet, E. F. Borro, J. R. P. Angel and R. M. E. Iling, Ap. J. 201, 624, (1975).
6. E. N. Parker, Origin of Magnetic Fields, Oxford Press, 767, 1979.
7. J. D. Jackson, Classical Electrodynamics, Example 8.13.
8. The derivation is straightforward but tedious. We have assumed that monopoles scatter electrons via the Rutherford scattering law with e replaced with gV. To obtain the energy loss formula we have followed the standard procedure of transforming from the lab system into the c.of m. system and after the collision transforming back to the lab system to find the gain or loss of energy suffered by the electrons. An integration to find the net dE/dx leads to equation (3).
9. E. N. Parker, Ap. J. 139, 951, (1964).

Appendix

Motions of Monopoles in Stellar Interiors

The motion of monopoles under the combined action of gravitational and magnetic forces in a stellar interior is represented by a two-dimensional model whose parameters are given below.

Gravitational forces F_g are given by

$$F_{xg} = -x \text{ and } F_{yy} = -y \quad (1)$$

Magnetic forces, F_{mag}, are given by

$$F_{xmag} = by[1/((1-x)^2+y^2)-1/((1+x)^2+y^2)] \quad (2a)$$

and

$$F_{ymag} = b[(1-x)/((1-x)^2+y^2)+(1+x)/((1+x)^2+y^2)]. \quad (2b)$$

where the coefficient b gives the relative strentgh of the magnetic to gravitational forces.

Equations 2a and 2b describe magnetic fields arising from parallel opposed currents flowing normal to the xy plane and centered at x=1 and x=-1.

Assuming drift directions along the resultant force lines and a persistence of the drift direction of 0.1 units, we have written a computer program to follow out and plot drift paths. In the absence of a detailed knowledge of current distributions in stellar interiors, only illusory precision would result from more elaborate modeling. Figs. 1a to 1d show the resulting drift paths for monopoles starting at points around a radius 2 units from the stellar center and with values of b, ranging from 0.5 to 10. For values of b below 0.6 there are no stable circulating orbits and the monopoles all drift to a trapping point. For values of b above 1, all monopoles drift to stable orbits circulating around the currents. Monopoles will therefore accumulate into the circulating orbits and remove magnetic field energy until b drops below ~ 0.6. Under standard conditions and with a current loop at 1/3 the stellar radius, this corresponds to final fields at the surface of < 1,500 Gauss for monopole masses less than $5 \cdot 10^{16}$ GeV.

Figure Captions

Fig 1. The circle is drawn at two units from the stellar center. Drift paths for monopoles starting at equally spaced intervals around the circumference are traced out. (a), (b), (c) and (d) are derived from relative field strengths of 0.5, 1.0, 2.0 and 10, respectively.

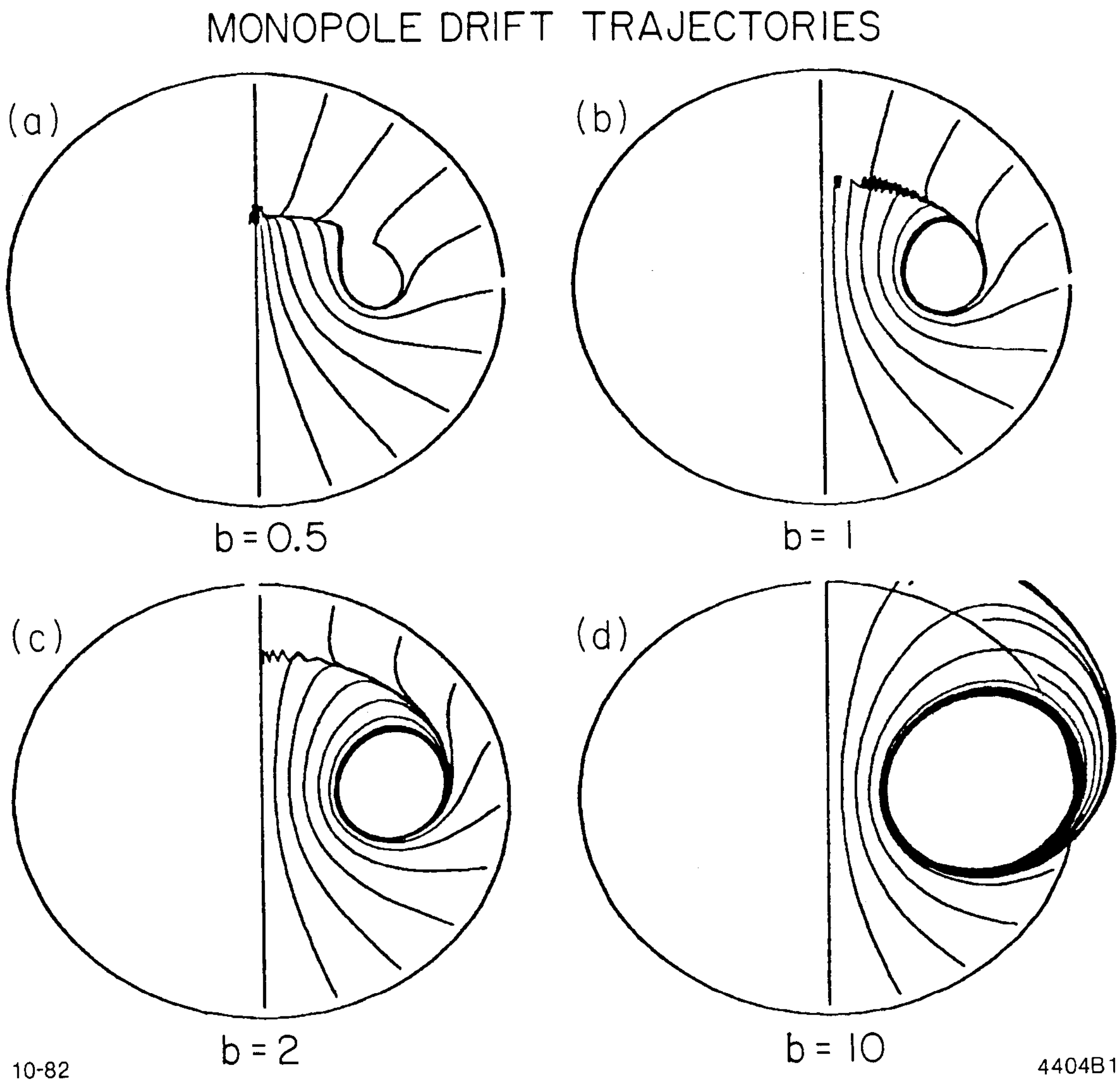

Fig. 1