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# Solar Monopoles and Terrestrial Neutrinos*

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## ABSTRACT

Magnetic monopoles captured in the core of the sun may give rise to a substantial flux of energetic neutrinos by catalyzing the decay of solar hydrogen. We discuss the expected neutrino flux in underground detectors under different assumptions about solar interior conditions. Although a monopole flux as low as $F_M \sim 10^{-24}$ cm$^{-2}$ sec$^{-1}$ sr$^{-1}$ could give rise to a neutrino flux above atmospheric background, due to $M\bar{M}$ annihilation this does not translate into a reliable monopole flux bound stronger than the Parker limit.

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Since they were first demonstrated to be generic features of grand unified theories, magnetic monopoles have been of enduring interest to theorists and experimentalists alike. Since a new generation of detectors, designed in part to search for these objects, is now being completed, it is useful to review the current limits on the monopole abundance. The strongest astrophysical bounds on the flux of superheavy monopoles come from the survival of pulsar magnetic fields,[1] $F_M \lesssim 10^{-24}$ cm$^{-2}$ sec$^{-1}$ sr$^{-1}$, and from monopole-catalyzed nucleon decay (Callan-Rubakov effect) in neutron stars,[2] $F_M \sigma_{28} \lesssim 10^{-21}$ cm$^{-2}$ sec$^{-1}$ sr$^{-1}$ or $F_M \sigma_{28} \lesssim 10^{-28}$ cm$^{-2}$ sec$^{-1}$ sr$^{-1}$ if main-sequence capture is included[3] [here the catalysis cross-section $\sigma_c = \sigma_{28} 10^{-28}$ cm$^2$]. These limits rely to some extent on untested properties of neutron stars, so it is natural to consider a better understood system which we can observe at close range, like the sun. In particular, it has been suggested that the Callan-Rubakov effect in the solar interior could give rise to an observable high-energy neutrino signal in underground detectors,[3][4] yielding a limit on the monopole flux comparable to (and more reliable than) the neutron star bounds.[4] In this talk, I review the expected neutrino signals from solar monopoles and critically examine the proposed limits.

We must first estimate the monopole population in the sun. The monopole stopping power in a stellar plasma is roughly[5] $dE/dx \simeq 10(g/g_D)^2 \rho (v_{mon}/c)$ GeV cm$^{-1}$, where $(g/g_D)$ is the monopole charge in Dirac units and $\rho$ is the density in gm cm$^{-3}$. From this, one can show[3] that the initial kinetic energy of the fastest monopole that can be captured in stars is $\frac{1}{2}mv_\infty^2 \lesssim 2.4 \times 10^{11} (g/g_D)^2$ GeV, approximately independent of stellar mass. Thus, a significant fraction of monopoles with the galactic virial velocity, $v_\infty \simeq 10^{-3}c$, are captured if their mass $m \lesssim 5 \times 10^{17} (g/g_D)$ GeV, which includes typical GUT-scale monopoles. A detailed calculation shows[3] that the total number captured over the lifetime of the sun is $N_\odot^{cap} = 3 \times 10^{41} F_M$, where $F_M$ is the galactic monopole flux in cm$^{-2}$ sec$^{-1}$ sr$^{-1}$.

Once captured in the sun, monopoles sink to the solar core, where they efficiently destroy nucleons. Given a solar nucleon density $n_n$, the catalysis rate per monopole is just $n_n \langle \sigma_c v \rangle$. Since the typical energy released in a catalysis reaction is of order the nucleon rest mass, the resulting neutrino flux at the earth is approximately

$$F_\nu^{cat} \simeq \frac{N_\odot^{mon} n_n m_n c^2 \langle \sigma_c v \rangle f_c}{4\pi R_{es}^2 \langle E_\nu \rangle} , \qquad (1)$$

where $f_c \sim 1$ is the average number of neutrinos produced per nucleon decay, $\langle E_\nu \rangle \sim 200$ MeV is the average neutrino energy, and $R_{es} = 1.5 \times 10^{13}$ cm is the mean earth-sun distance. The catalysis cross-section is expected to scale as $v^{-1}$, which would yield $\langle \sigma v/c \rangle = \sigma_{28} 10^{-28}$ cm$^2$. However, Arafune and Fukugita[6] found that the cross-section on hydrogen is enhanced by a velocity-dependent factor $F(v/c) \simeq 170(10^{-3} c/v)$. Using $v/c \simeq 10^{-3}$ for nucleons in the solar interior (the monopole thermal speeds are negligible), from Eqn. (1) we find an expected neutrino flux $F_\nu^{cat} \simeq (N_\odot^{mon} \sigma_{28}/10^{17})$ cm$^{-2}$ sec$^{-1}$. Using the limit on the flux of high energy neutrinos from proton decay detectors, $F_\nu(E_\nu \gtrsim 200 \text{ MeV}) \lesssim 1$ cm$^{-2}$ sec$^{-1}$, we obtain an upper bound on the number of monopoles in the sun,

$$N_\odot^{mon} \sigma_{28} \lesssim 10^{17} . \qquad (2)$$

If we assume the number of monopoles in the sun is just the number captured, $N_\odot^{mon} = N_\odot^{cap} \simeq 10^{41} F_M$, we find the stringent "solar catalysis flux bound" $F_M \sigma_{28} \lesssim 10^{-24}$ cm$^{-2}$ sec$^{-1}$ sr$^{-1}$.

The final assumption above, while seemingly plausible, neglects the fact that monopoles and antimonopoles in the sun are likely to annihilate each other. Since they are so heavy, monopoles cluster deep in the core; the characteristic radius of the solar monopole distribution supported by thermal pressure is only $r_{TH} \simeq 100 m_{16}^{-1/2}$ cm, where the monopole mass $m_M = m_{16} 10^{16}$ GeV. For conditions in the solar center, it turns out that three-body annihilation processes dominate,[7] with cross-section $\langle \sigma_{ann} v \rangle = n_M m_M^{-1/2} \alpha^{-5} (kT)^{-9/2} \simeq 9 \times 10^{-29} m_{16}^{-1/2} n_M$ sec$^{-1}$. The solar monopole number approaches a fixed point where the annihilation and capture rates balance, given by $N_\odot^{mon} = N_{TH} \simeq 10^{22} m_{16}^{-1/2} F_M^{1/3} \ll N_\odot^{cap}$.

Combining this with the limit of Eqn. (2) yields a much weaker but more reliable solar catalysis bound on the monopole flux, $F_M\sigma_{28} \lesssim 10^{-15}$ cm$^{-2}$ sec$^{-1}$ sr$^{-1}$ [see Fig. 1]. Note that this is comparable to the Parker bound,[8] $F_M \lesssim 10^{-16}$ cm$^{-2}$ sec$^{-1}$ sr$^{-1}$, coming from the survival of the galactic magnetic field.

If $M\bar{M}$ annihilation is so prolific in the sun, we may wonder whether annihilation rather than catalysis could generate an observable neutrino signal. The neutrino flux from monopole annihilation is obtained from Eqn. (1), with the replacements $n_n \to n_M$, $m_n \to m_M$, $\sigma_c \to \sigma_{ann}$, $f_c \to f_{ann}$, and using $N_{\odot}^{mon} = N_{TH}$. Assuming $f_{ann} \sim 1$, we find a neutrino flux $F_\nu^{ann} \simeq m_{16}^{3/2}(F_M/10^{-16})^{2/3}$. Again applying the detector limit on high energy neutrinos, one obtains a 'solar annihilation bound' comparable to the Parker limit.

For completeness, we should note that the occurence of $M\bar{M}$ annihilation in the sun itself depends on unknown conditions deep in the solar core. For example, a static magnetic field of strength $B \gtrsim 400$ Gauss would separate the monopole and antimonopole distributions sufficiently to prevent annihilation. Such a field would have to be primordial (no dynamo operates in the convectively stable core) and would have to have a coherence length $l \gtrsim 10^9$ cm in order to be stable against resistive decay on the solar lifetime. In addition, since magnetic flux tubes are buoyant and generally diffuse toward the stellar surface, the field must be sufficiently weak to be anchored at the center for $10^9$ years. Although this is a possible mechanism for $M\bar{M}$ separation, and *might* lead to a large neutrino signal from catalysis, it is by no means highly probable. As a result, magnetic fields cannot be invoked to 'save' the more stringent solar catalysis bound.

We conclude that underground observations of the high energy neutrino flux place bounds on the solar monopole abundance which are competitive with the Parker limit. These solar bounds cannot reliably be made more restrictive. In particular, they do not preclude the direct detection of monopoles by large detectors such as MACRO. On the other hand, *if* magnetic fields separate monopoles from antimonopoles in the solar core, a monopole flux as low as $F_M \sim 10^{-24}$

$cm^{-2}\ sec^{-1}\ sr^{-1}$ would generate a high energy neutrino flux from catalysis which should be separable from atmospheric background.

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## FIGURE CAPTIONS

1) The solar monopole abundance as a function of the monopole flux. $N_{\odot}^{cap}$ is the number captured over the solar lifetime, and $N_{TH}$ is the equilibrium solar abundance taking annihilations into account. The long horizontal line is the solar catalysis limit; the short horizontal shows the neutron star catalysis limit for comparison.

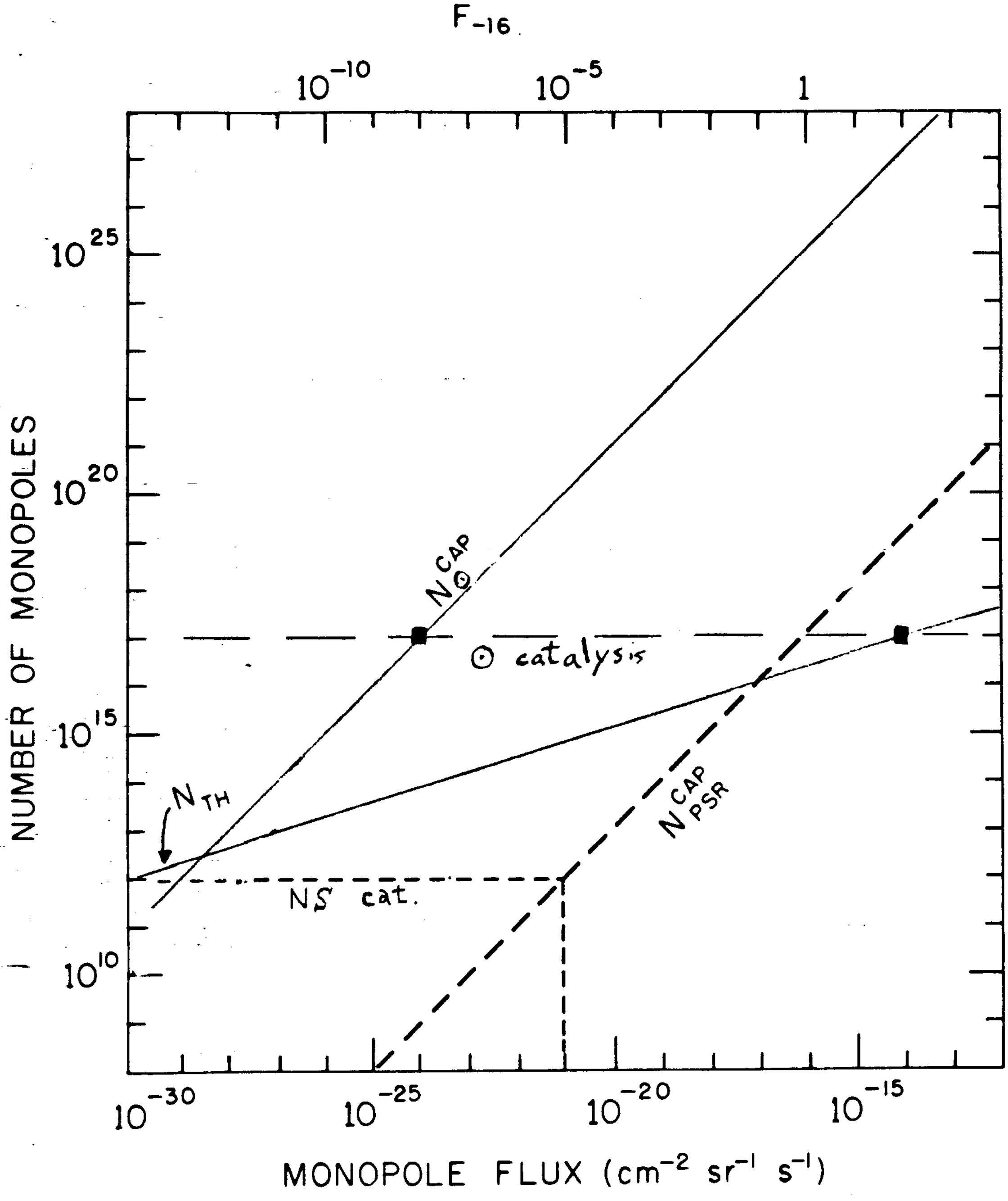
F₋₁₆
$10^{-10}$
$10^{-5}$
1
$10^{25}$
$10^{20}$
$10^{15}$
$10^{10}$
NUMBER OF MONOPOLES
$N_{\odot}^{CAP}$
⊙ catalysis
$N_{TH}$
NS cat.
$N_{PSR}^{CAP}$
$10^{-30}$
$10^{-25}$
$10^{-20}$
$10^{-15}$
MONOPOLE FLUX ($cm^{-2}$ $sr^{-1}$ $s^{-1}$)

Fig. 1