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MONOPOLES, COSMOLOGY, AND ASTROPHYSICS--UPDATE 1985

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ABSTRACT

I briefly review the cosmological predictions for the monopole abundance--somewhere between too many and too few and the astrophysical constraints on the present flux of relic monopoles--at most 1 per football field per year and if monopoles catalyze nucleon decay at most 1 per large city per year. Due to the effects of cosmic magnetic and gravitational fields any monopoles present should be moving with speeds of order at least a few $\times\ 10^{-3}$ c relative to the earth.

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INTRODUCTION

The superheavy magnetic monopoles predicted by unified theories remain extremely interesting and enigmatic objects. They offer one of the few windows to physics at energies much greater than 1 TeV and to the earliest moments of the Universe ($t \lesssim 10^{-34}$sec). Theory still provides no useful or reliable prediction of their relic abundance, and the very stringent astrophysical bounds based upon the survival of astrophysical magnetic fields and catalysis of nucleon decay in neutron stars remain intact after very careful scrutiny (summarized in Fig. 1). In this article I present a brief review of the current situation, a situation which has not changed appreciably in the past few years. I refer the interested reader to the longer and more complete reviews in refs. 1-5.

WHAT IS A SUPERHEAVY MONOPOLE?

A superheavy magnetic monopole is a stable, nontrivial configuration of gauge and Higgs fields.[6,7] Such configurations exist in a gauge theory whenever a semi-simple group (e.g., SU(5), SO(10), E6, etc.) is broken down to a group with an explicit U(1) factor, e.g., SU(3)×SU(2)×U(1). The three conspicuous features of the 't Hooft-Polyakov monopole are: (1) large mass, of order M/α (M = the symmetry breaking scale, α = gauge coupling constant)--for SU(5), $m_M \simeq 10^{16}$ GeV; (2) hefty magnetic charge, $g = ng_D$, where n is an integer and $g_D = 1/2e \simeq 69e$ is the Dirac charge; (3) the remarkable ability to catalyze nucleon decay either via the Callan-Rubakov process[8,9] or via the weak anomaly.[10,11]

The cross section for catalysis via the Callan-Rubakov process is expected to be of the order of a strong interaction cross section

$$(\sigma v)_{\Delta B} = \sigma_{-28} 10^{-28} cm^2 \quad , \tag{1}$$

while catalysis via the weak anomaly is thought to be suppressed by mixing angles and other kinematic factors, and is likely to many orders of magnitude smaller ($\sigma_{-28} << 1$). Which monopoles catalyze nucleon decay via the Callan-Rubakov process and which via the weak anomaly? To over-simplify somewhat, if the physics at the core of the monopole does not conserve baryon number (as is the case in the simplest GUTs and simplest symmetry breaking schemes), then the monopole catalyzes nucleon decay via the Callan-Rubakov process. If the physics at the core of the monopole does not violate baryon number (as is the case in more complicated SSB schemes, e.g., the Z_2 monopoles of SO(10)),[12] then the monopole only catalyzes nucleon decay via the weak anomaly. These three properties lead to monopoles having interesting (and often conspicuous) astrophysical consequences, which in turn lead to the very stringent astrophysical bounds on the present flux of monopoles.

I should emphasize that although superheavy magnetic monopoles are expected to have all three of these properties, the only property that a magnetic monopole must necessarily have is a magnetic charge which is a multiple of the Dirac charge.

BIRTH

There are certainly no contemporary sites, astrophysical or otherwise, where objects of mass 10^{16} GeV or so can be produced. Thus we must look to the early Universe ($t \lesssim 10^{-34}$sec, $T \gtrsim 10^{14}$GeV) as the birthing site for these extremely interesting and important objects. There are two basic ways that monopoles can be produced in the early Universe: (1) as topological defects in the SSB transition--the so-called Kibble process[13]; (2) thermal pair production in very energetic particle collisions.[14-16] Unless the SSB phase transition occurs at a very low temperature ($T << 10^{10}$GeV) or the symmetry breaking pattern is very complicated, process (1) leads to a severe overproduction of monopoles--for $M \simeq 10^{14}$ GeV, so many are produced by this process that the Universe reaches a temperature of 3K at the very tender age of 30,000 yrs (refs. 1-5, 17-20). Subsequent annihilation is not efficient enough to reduce the number of monopoles to a safe level[17]. [However, Wasserman[21] has recently reexamined this question and raises the possibility that annihilations may be enhanced by the presence of the $e^{\pm}$ plasma, in which case they may be able to reduce the initial abundance to a safe level.]

If the SSB phase transition is inflationary,[22-24] then the overproduction is avoided as process (1) leads to less than 1 monopole in the observable Universe. In more complicated inflationary scenarios monopoles may be produced by process (1) during the inflationary epoch itself (toward the end)[25] or in a subsequent phase transition[26]. Whether or not an interesting number of monopoles can be produced in this way remains to be seen. By interesting, I mean large enough to be potentially observable, but not so as to be ruled out by the astrophysical constraints.

Process (2) occurs even if the Universe underwent inflation. However, the number of monopoles produced this way is expected to be exponentially small (and exponentially uncertain)--monopoles cannot be produced until SSB has occurred, $T < M$, and $m_M \simeq M/\alpha \simeq 100M$, and so the number expected is:

$$n_M \propto \exp(-2m_M/M) \propto \exp(-\text{few } 100). \qquad (2)$$

Although thermal production does not look too promising from a monopole hunter's point of view, the uncertainties are such that it is not impossible that an interesting abundance could have been produced this way.[14,27,28]

To summarize the present status of the theoretical predictions for the monopole abundance--Pick a number, any number! In the absence of a meaningful prediction for the monopole abundance all we can do is treat the monopole abundance as a free parameter. The following are useful formulae:

$$\langle F\rangle \simeq 10^{10}(n_M/s)(v_M/10^{-3}c)\text{cm}^{-2}\ \text{sr}^{-1}\ \text{s}^{-1}, \qquad (2a)$$

$$\simeq (n_M/n_B)(v_M/10^{-3}c)\text{cm}^{-2}\ \text{sr}^{-1}\ \text{s}^{-1}, \qquad (2b)$$

$$\simeq 3\times10^{-15}\Omega_M h^2(v_M/10^{-3}c)(10^{16}\text{GeV}/m_M)\ \text{cm}^{-2}\ \text{sr}^{-1}\ \text{s}^{-1}, \qquad (2c)$$

where n_M, n_γ, n_B, and s ($\simeq$ 7.1 n_γ) are the average monopole number density in the Universe, the photon number density, the baryon number density, and the entropy density; $\langle F \rangle$ is the average monopole flux in the Universe, $\Omega_M \equiv \rho_M/\rho_c$ is the fraction of critical density contributed by monopoles, $\rho_c = 1.88h^2 \times 10^{-29}$g cm^{-3} is the critical density, $h = H_o/(100$ km sec^{-1} Mpc$^{-1})$, and v_M is the typical monopole velocity (to be discussed in more detail later).

The local monopole number density and flux (i.e., in the vicinity of the solar system) may be larger than the average values of these quantities in the Universe if, for example, monopoles are concentrated in the galaxy. Denote the enhancement factor by f:

$$F_{GAL} \simeq f \langle F \rangle \ . \tag{3}$$

Naively, we might expect $f \simeq \rho_{GAL}/\bar{\rho} \simeq 10^5$--which is a rather healthy factor (here $\bar{\rho}$ is the average density of the Universe). I will return to this issue later.

WHERE ARE THEY TODAY?

Because monopoles are so heavy their internal thermal velocity dispersion is tiny: $\langle v_M^2 \rangle^{1/2} \ll 1$ cm sec^{-1}. Since they are effectively collisionless they have only their velocity dispersion to support them against gravitational collapse. Due to their tiny velocity dispersion they should be unstable to gravitational collapse on virtually all scales. However, as they are effectively collisionless they cannot dissipate their gravitational energy and condense into tightly bound objects whose formation involved dissipation, such as the disks of spiral galaxies, stars, etc. [Later, after stars have formed they can capture monopoles which impinge upon them--an issue to which I shall return.]

Naively then, we would expect to find monopoles in all structures whose formation did not involve dissipation, from galactic halos to clusters of galaxies to superclusters. The density contrasts for these objects are about 10^5, 100, and a few respectively. Within these objects we would expect $f \simeq \rho/\bar{\rho}$. Since we live in a galaxy this suggests a local enhancement $f \simeq 10^5$ over the average monopole flux in the Universe. However the magnetic field of our galaxy will eject monopoles less massive than about 10^{20} GeV in less than the age of the galaxy.[32] Therefore, we should not expect to find a concentration of monopoles in our locality. The magnetic fields observed in clusters of galaxies are only potent enough to eject light monopoles, those lighter than about 10^{15} GeV.[37]

Since our galaxy is not a member of a cluster and is only on the outskirts of the Virgo supercluster where the density contrast is about 1, we would expect the monopole flux in our vicinity to be due primarily to monopoles which just happen to be passing through the galaxy (and perhaps an equal number which are bound to the Virgo supercluster). Thus, the local flux should be about equal to the average cosmic flux ($f \simeq 1$).

[It has been suggested that the flux of monopoles in the solar system could be enhanced by a very large factor[29]--up to 10^6, due to a cloud of monopoles orbiting the sun, monopoles which, over the life of the solar system, were captured by the sun. A more careful estimate[30] of this effect indicates that an enhancement of this kind might be at most a factor of a few.]

HOW FAST ARE THEY MOVING?

From the point of view of detecting monopoles their speed relative to the detector is a very important issue. As I discussed above their thermal velocities are absolutely negligible. However, they will be accelerated by any gravitational and magnetic fields they encounter. The typical peculiar (meaning relative to the Hubble flow) velocities of objects in the Universe are of order $10^{-3}c$--implying typical monopole-galaxy velocities of this magnitude. Monopoles will be accelerated by the gravitational fields of galaxies--to $O(10^{-3}c)$, of clusters--to $O(\text{few} \times 10^{-3}c)$, and of superclusters--to $O(10^{-2}c)$. Monopoles will also be accelerated by magnetic fields. The intragalactic magnetic field strength is only known to be less than 3×10^{-11} G (ref. 31), and will accelerate monopoles to velocities of

$$v_M \simeq 3 \times 10^{-4}c \; (B/10^{-11}G)(10^{16}GeV/m_M). \tag{4}$$

The galactic magnetic field will accelerate monopoles otherwise at rest to velocities of[32]

$$v_M \simeq 3 \times 10^{-3}c \; (10^{16}GeV/m_M)^{1/2}. \tag{5}$$

Of course earth-based detectors are not at rest themselves, having velocity components due to the earth's rotation--$2 \times 10^{-6}c$, the motion of the earth around the sun--$10^{-4}c$, and the orbital motion of the solar system through the galaxy--$7 \times 10^{-4}c$. I have summarized all of these velocity components for monopoles and monopole detectors in Table 1.

From the above discussion and the Table it is clear that one should expect monopole-detector relative velocities of at least a few $\times 10^{-3}c$. This is an important consideration which must be taken into account when designing the velocity acceptance of a detector. [In the very unlikely case that most of the monopole flux in our neighborhood is due an orbiting monopole cloud, typical monopole velocities would be of order a few $\times 10^{-4}c$, implying monopole-detector relative velocities of order a few $\times 10^{-4}c$.]

Although monopoles would not be in objects such as stars, planets, etc. ab initio, because the formation of these objects clearly involved dissipation, they can be captured by these objects. Monopoles passing through matter lose energy by electronic interactions, hadronic interactions, magnetic interactions, and nuclear interactions. The electronic interactions (energy loss due to the eddy currents they induce) are usually the most important loss mechanism[33]. Monopoles less massive than about 10^{20}GeV will lose sufficient energy when passing through neutron stars and white dwarfs to become captured. Monopoles less massive than about 10^{18}GeV lose sufficient in main sequence stars to become captured. Jupiter-sized objects can stop monopoles as massive as 10^{16}GeV, and the earth can stop very slow moving or light monopoles ($\lesssim 10^{15}$ GeV). The number of monopoles captured by an astrophysical object depends upon its gravitational capture cross, the monopole flux, and the time interval τ:

$$N_{CAP} \simeq (4\pi R^2)(\pi\text{-sr})(1 + 2GM/Rv_M^2)\ F\ \tau\ , \tag{6a}$$

$$\simeq 3.2\times10^{24}(F/10^{-16}\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1})(R/R_\odot)^2\ (\tau/10^9\text{yr})[(1 + 2GM/Rv_M^2)/5.3], \tag{6b}$$

where R and M are the radius and mass of the object, and $1 + 2GM/RV_M^2$ is the ratio of the gravitational to the geometric cross section (whose value is 5.3 for a 1 solar mass star). Once captured monopoles will sink to the center of the object and be supported against gravity by their thermal velocity dispersion or magnetic fields that may be present.[34] The number of monopoles residing in the object also depends upon the importance of monopole-antimonopole annihilations. Finally, I should mention that monopole capture does not deplete the cosmic stock of monopoles appreciably--even within the galaxy the mean free path of a monopole is 10^{42}cm.

ASTROPHYSICAL IMPLICATIONS--FLUX LIMITS

Because of their three extraordinary properties--macroscopic mass, hefty EM charge, and ability to catalyze nucleon decay, monopoles, if present even in small numbers, will make themselves astrophysically conspicuous. Their potential conspicuousness leads to stringent astrophysical bounds on their flux (and, if we can be very clever, astrophysics may provide us with very sensitive monopole detectors).

First consider the mass they contribute. Although we do not have precise knowledge of Ω (the ratio of the cosmic mass density to the critical density), estimates of the deceleration parameter q_o and the age of the Universe strongly suggest that: $\Omega h^2 < 1$. This in turn places a limit on the average flux of monopoles in the Universe:

$$\langle F \rangle \lesssim 3 \times 10^{-15}(10^{16}\mathrm{GeV}/m_M)\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}. \tag{7}$$

Recall that the local flux could be enhanced by a factor f which could be as large as 10^5.

Monopoles cannot contribute more mass density locally than we observe[35]

$$\rho_{LOCAL} \simeq 10^{-23}\ \mathrm{g\ cm}^{-3}$$

This leads to the flux limit

$$F_{GAL} \lesssim 10^{-9}(10^{16}\mathrm{GeV}/m_M)\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}\ . \tag{8}$$

In fact we can do better than this. By carefully modelling the galaxy, Bahcall[35] finds that the contribution of the halo material to the local mass density can be no more than about 1/30 of the total mass density, i.e., the disk component dominates the local mass density. [Remember, if monopoles are clustered in the galaxy they must be in the halo since they have no mechanism for dissipating their gravitational energy and condensing into the disk.] This leads to the more stringent limit

$$F_{GAL} \lesssim 3 \times 10^{-11}\ (10^{16}\mathrm{GeV}/m_M)\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}. \tag{9}$$

I should re-emphasize that the bound based upon the average flux of monopoles in the Universe is probably the relevant one as the galactic magnetic field will keep all but the most massive monopoles from clustering in the galaxy.

Next magnetic monopoles and astrophysical magnetic fields. Because of their hefty magnetic charge monopoles will respond to any magnetic fields they may encounter and in the process usually gain KE--of course, this must occur at the expense of the magnetic field energy. Parker pioneered using this simple principle to place limits on the flux of monopoles.[36] The basic idea being that monopoles tend to drain astrophysical magnetic fields, with a damping time which is inversely proportional to the monopole flux. Survival of an astrophysical magnetic field requires that the damping time due to monopoles be no shorter than the time required to regenerate the field. He applied the argument to the galactic magnetic field (strength 3×10^{-6} G and coherence length 300 pc) which is believed to be produced by dynamo action (which converts KE embodied in the differential rotation of the galaxy into magnetic field energy) and whose regeneration time is order 100 Myr. The limit which follows is[32]

$$F_{GAL} \lesssim 10^{-15}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}\ , \quad (m_M \lesssim 10^{17}\ \mathrm{GeV}) \qquad (10a)$$

$$F_{GAL} \lesssim 10^{-15}\ (m_M/10^{17}\ \mathrm{GeV})\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}\ , \quad (m_M \gtrsim 10^{17}\ \mathrm{GeV}) \qquad (10b)$$

Rephaeli and Turner[37] applied the same argument to the survival of the weaker magnetic fields which are observed in rich clusters (10^{-7} G and coherence length ≃ 1 Mpc). The result is a much more stringent bound

$$\langle F \rangle \lesssim 10^{-18}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}\ , \qquad (11)$$

which, however, is somewhat less reliable than the Parker bound as our knowledge of intracluster magnetic fields is not as secure as that of galactic magnetic fields.

Other authors have applied Parker's logic to the magnetic fields in white dwarfs, neutron stars, and peculiar A stars.[38-40] Because of the additional assumptions involved, these bounds while more stringent than the Parker bound, are very much less certain.

The implicit assumption made in deriving Parker-type bounds is that monopoles respond incoherently to the astrophysical magnetic field. If they can respond coherently (as in the case of magnetic plasma oscillations), then the KE they extract from the magnetic field energy will be returned a half cycle later.[32,41-43] In this case the field energy is not drained, but only borrowed for a half cycle, and the bound in question can be circumvented. In fact, in some sense, the monopoles are participating in the maintenance of the magnetic field.

The key issue with regard to evading damping then is that of coherence. In general this translates to a condition on the phase velocity of the oscillations:

$$v_{ph} \gtrsim \langle v_M^2 \rangle^{1/2}$$

The phase velocity of the oscillations is just $v_{ph} = (\omega_p/2\pi)\ell$ where ℓ is the characteristic length scale of the mode and $\omega_p^2 = 4\pi g^2 n_M/m_M$ is the magnetic plasma frequency. The internal velocity dispersion of the monopoles depends upon the circumstances; for a galactic halo of monopoles one expects it to be of order the virial velocity of the galaxy--10^{-3} c.

The condition that v_{ph} be greater than $\langle v_M^2 \rangle^{1/2}$ results in a lower bound to the monopole flux (if coherent effects are to be important):

$$F \gtrsim \frac{1}{4} m_M \langle v_M^2 \rangle^{3/2} (g\ell)^{-2} . \tag{12}$$

For the galaxy that bound is

$$F_{GAL} \gtrsim 10^{-13} (m_M/10^{16}\mathrm{GeV})(1\mathrm{kpc}/\ell)^2 \mathrm{~cm}^{-2} \mathrm{~sr}^{-1} \mathrm{~s}^{-1}. \tag{13}$$

While it is possible that the Parker bound can be circumvented by coherent effects, I think that it is an unlikely possibility. There are many issues to be addressed before this can be considered as a serious possibility: how such oscillations got set up in the first place; how the required spatial and temporal coherence is maintained in the face of the inhomogeneities known to exist in the galaxy; and how the numerous damping mechanisms can be avoided. The most difficult huddle at present is the observational one--the present experimental limits on the monopole flux preclude the scenario unless the monopole mass is much less than 10^{16} GeV.

The most spectacular effect associated with superheavy magnetic monopoles is their apparent ability to catalyze nucleon decay at a prodigious rate.[8,9] The rate of energy release by this process is enormous:

$$dE/dt \simeq 10^{18} \text{ ergs sec}^{-1}\, N_M\, (\rho_N/3\times10^{14} \text{ g cm}^{-3})\, \sigma_{-28} , \qquad (14)$$

where ρ_N is the local nucleon density, and N_M is the number of monopoles. In a neutron star the energy release is 10^{18} ergs sec^{-1} per monopole--a single monopole catalyzing nucleon in a neutron star produces almost as much power as is consumed by all the inhabitants of our planet! How does this process manifest itself in the cosmos?

Astrophysical objects such as stars, planets, <u>etc.</u> capture some or all of the monopoles that strike them. Once captured they sink to the center and accumulate there at a rate proportional to the monopole flux. There they catalyze nucleon decay releasing about 1 GeV per catalysis event. The energy is thermalized and radiated--in the IR (for planets), visible (for main sequence stars), UV (for white dwarfs), or X-ray (for neutron stars). In the process, some of the energy may also be released in neutrinos.

Using the observed photon flux from a variety of astrophysical objects--the earth[44], Jupiter[44], white dwarfs[45] and neutron stars,[46-49] one can place very stringent limits on the flux of monopoles in the galaxy. The most stringent and I believe most reliable limit comes from neutron stars:

$$F_{GAL} \leq 10^{-21} \sigma_{-28}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}. \qquad (15)$$

I say most reliable because the various uncertainties, both due to astrophysics and particle physics, are better understood and believed to be the smallest for neutron stars. For example, when the catalysis process involves nuclei (as it would in planets or white dwarfs) there are angular momentum barriers and the question of whether the monopole gobbles the entire nucleus or just a few nucleons[50]. At small monopole-nucleon relative velocities there may be threshold effects--in a neutron star the relative velocities are of order the speed of light.

Monopole-antimonopole annihilations are almost certainly not important in neutron stars[51]. Owing to their high densities, neutron stars can capture monopoles at least as massive as 10^{20} GeV. The neutron star limit quoted above is actually based on a triad of observations: measured X-ray fluxes (or upper limits) from individual objects[48]; the negative results of serendipitious X-ray searches for bright, nearby neutron stars[47]; and the use of the measured intensity of the soft X-ray background to limit the integrated luminosity of all the old neutron stars in the galaxy[49]. In addition, all of the 'astrophysical outs' have been carefully examined and found not to be important (e.g., the possibility that neutron stars would eject the monopoles they capture, that annihilations might be important, or that essentially all the catalysis energy would be released in neutrinos). A review of the neutron star catalysis limits is given in ref. 49. I might mention that the limit based upon catalysis in white dwarfs is also very stringent[45]

$$F_{GAL} \lesssim 3 \times 10^{-18} \sigma_{o}^{-1} \ \mathrm{cm}^{-2} \ \mathrm{sr}^{-1} \ \mathrm{s}^{-1}, \tag{16}$$

and the uncertainties are not too much worse than for neutron stars--and involve different physics and astrophysics.

Main sequence stars capture significant numbers of monopoles[34] (so long as they are less massive than 10^{18} GeV); see Fig. 2. The main sequence progenitor of a neutron star captures 10^6 or so times as many monopoles as the neutron star itself does. If one takes into account the very likely presence of these monopoles in neutron stars, the limit quoted above improves by a factor of about 10^6:

$$F_{GAL} \lesssim 10^{-27} \sigma_{-28}^{-1} \ \mathrm{cm}^{-2} \ \mathrm{sr}^{-1} \ \mathrm{s}^{-1} \tag{17}$$

However, it is only fair to mention the additional uncertainties involved--do the monopoles annihilate in the main sequence progenitor? do they get ejected in the process of the formation of the neutron star?, to mention two.

EXOTIC ASTROPHYSICAL MONOPOLE DETECTORS

If monopoles do catalyze nucleon decay the neutron star bound all but precludes building an earth-based detector to find them--a flux of 10^{-21} cm^2 sr^{-1} sec^{-1} corresponds to one monopole through a large city per year! We may then have to turn to astrophysical objects as detectors. In the next decade or so there will be a number of soft X-ray and extreme UV satellite-based detectors operating. Soft X-ray and extreme UV are the optimal bands for detecting neutron stars heated by monopole catalysis. By observing a number of nearby, old neutron stars it may be possible to 'detect monopoles' by their heating effect on these objects, thereby providing us with extremely sensitive monopole detectors.

Another idea for an astrophysical detector is to detect the monopoles which are residing in the sun.[44,52,53] The sun captures a significant number of monopoles--about

$$N_{CAP} \simeq 10^{25}(F_{GAL}/10^{-16}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}).$$

If they avoid annihilation (for a discussion of this see ref. 34) they will be catalyzing nucleon decays in the sun and be producing neutrinos with energies of 10's of MeV (from the decays of π's and μ's produced by catalysis). These neutrinos may be detectable in a large, underground earth-based detector such as IMB, Kamiokande, or the Homestake solar neutrino detector (how appropriate!). Preliminary estimates of the signal however suggest that even if all the monopoles captured avoid annihilation, the smallest detectable flux would be about $10^{-20}\sigma_{-28}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$, which is more than likely ruled out by the neutron star limits. The idea however warrants further study.

CONCLUDING REMARKS

What have we learned about GUT monopoles in the past five years or so? (1) They are exceedingly interesting objects, which if detected would provide us with a unique window to both the earliest moments of the Universe and to physics at the very highest energies. (2) They remain one of the few generic predictions of GUTs which we can hope to verify in our low energy environment. (3) At present there is no believable prediction for the flux of relic, superheavy monopoles. (4) Based upon astrophysical considerations we can be reasonably certain that the monopole flux is small. Since it is not obligatory that monopoles catalyze nucleon decay at a prodigious rate, the most stringent and reliable upper bound to the monopole flux is the Parker bound: $F_{GAL} \lesssim 10^{-15}$ cm^{-2} sr^{-1} s^{-1} (for $m_M \lesssim 10^{17}$ GeV). Note that this is not a prediction for the flux. In fact, it is very likely that the flux must be significantly smaller, $F \lesssim 10^{-18}$ cm^{-2} sr^{-1} s^{-1}, based on the survival of intracluster magnetic fields, and if monopoles catalyze nucleon decay, $F_{GAL} \lesssim 10^{-21}$ cm^{-2} sr^{-1} s^{-1}. (5) There is every reason to believe that monopoles are moving (relative to the earth) with typical velocities of <u>at least</u> a few $\times 10^{-3}$ c.

In spite of the somewhat bleak theoretical situation (with respect to monopoles) I still believe that monopoles are worth hunting. The risks may be very great, but the potential payoffs are even greater!

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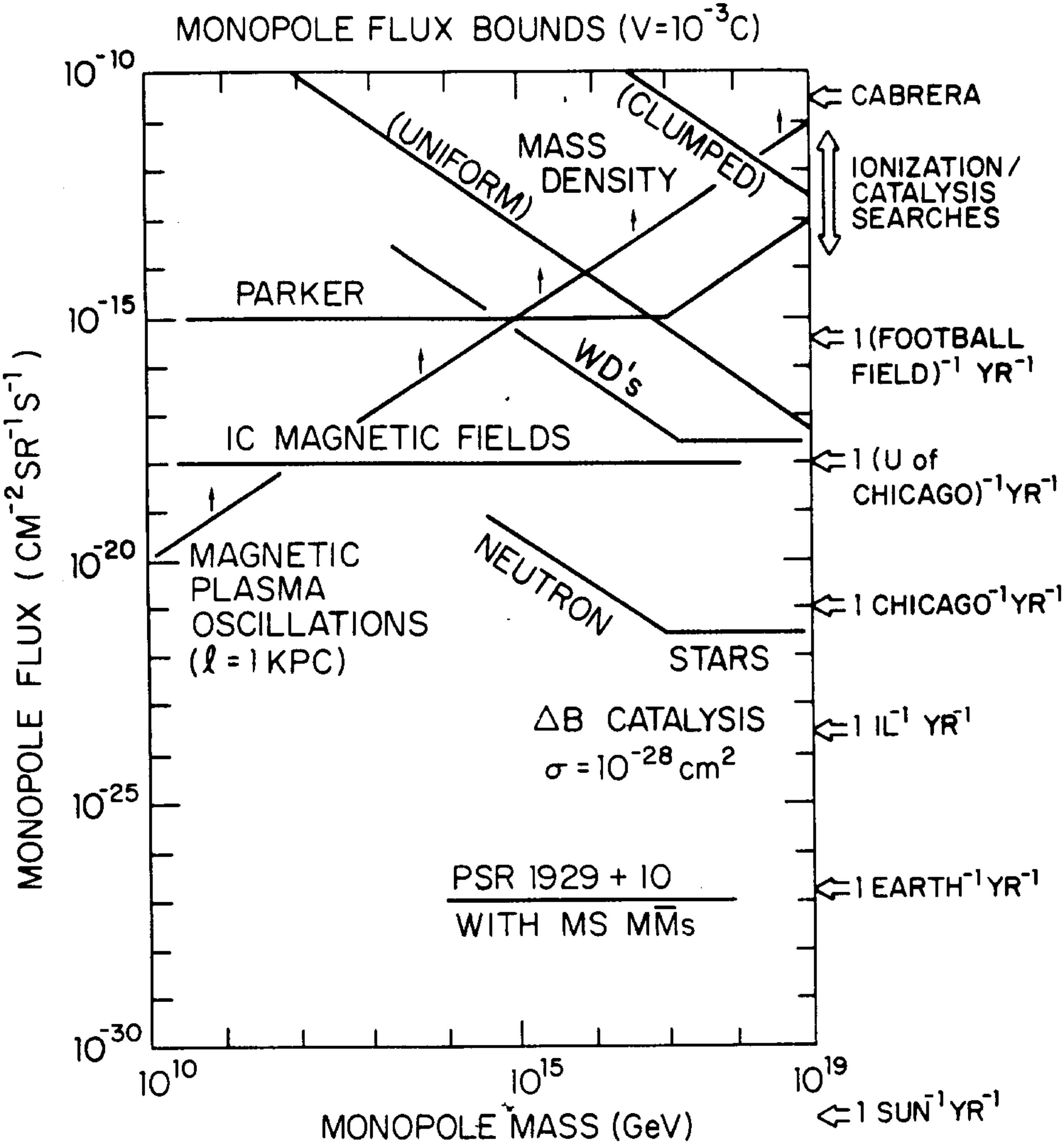
Figure Captions

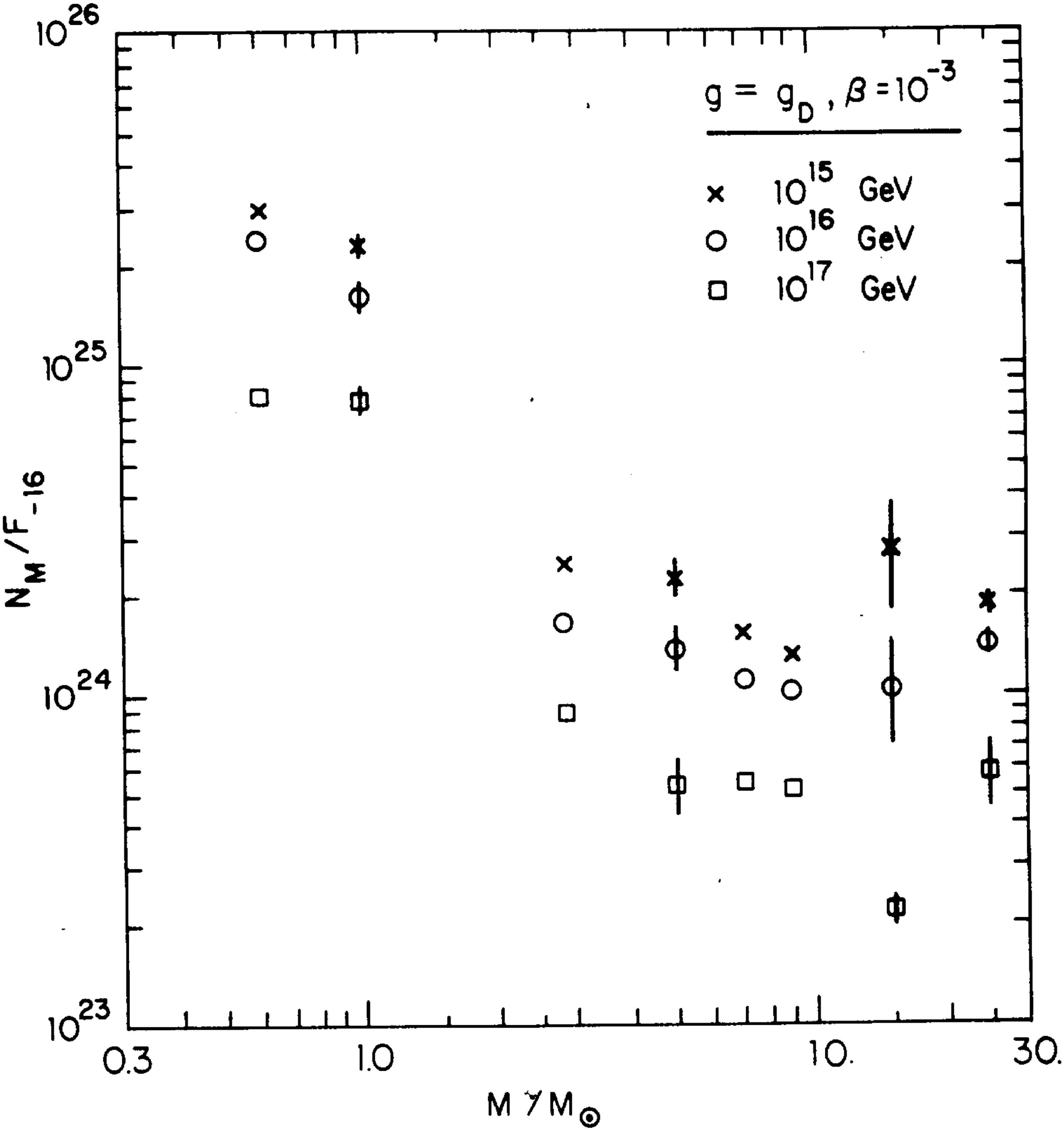
Fig. 1 - Summary of the astrophysical and cosmological monopole flux limits discussed in the text. Wherever necessary a monopole velocity of 10^{-3} c was assumed. The line labeled 'magnetic plasma oscillations' is the minimum flux required such that it is possible for coherent monopole effects to prevent the damping of the galactic magnetic field.

Fig. 2 - Number of monopoles (with Dirac charge) captured by main sequence stars during their lifetimes. Here $v_M = 10^{-3}$ c and $F_{-16} = F_{GAL}/(10^{-16}\ cm^{-2}\ sr^{-1}\ s^{-1})$. Detailed stellar models were used and the monopole energy loss was assumed to be due to electronic interactions only; for more details see ref. 34.

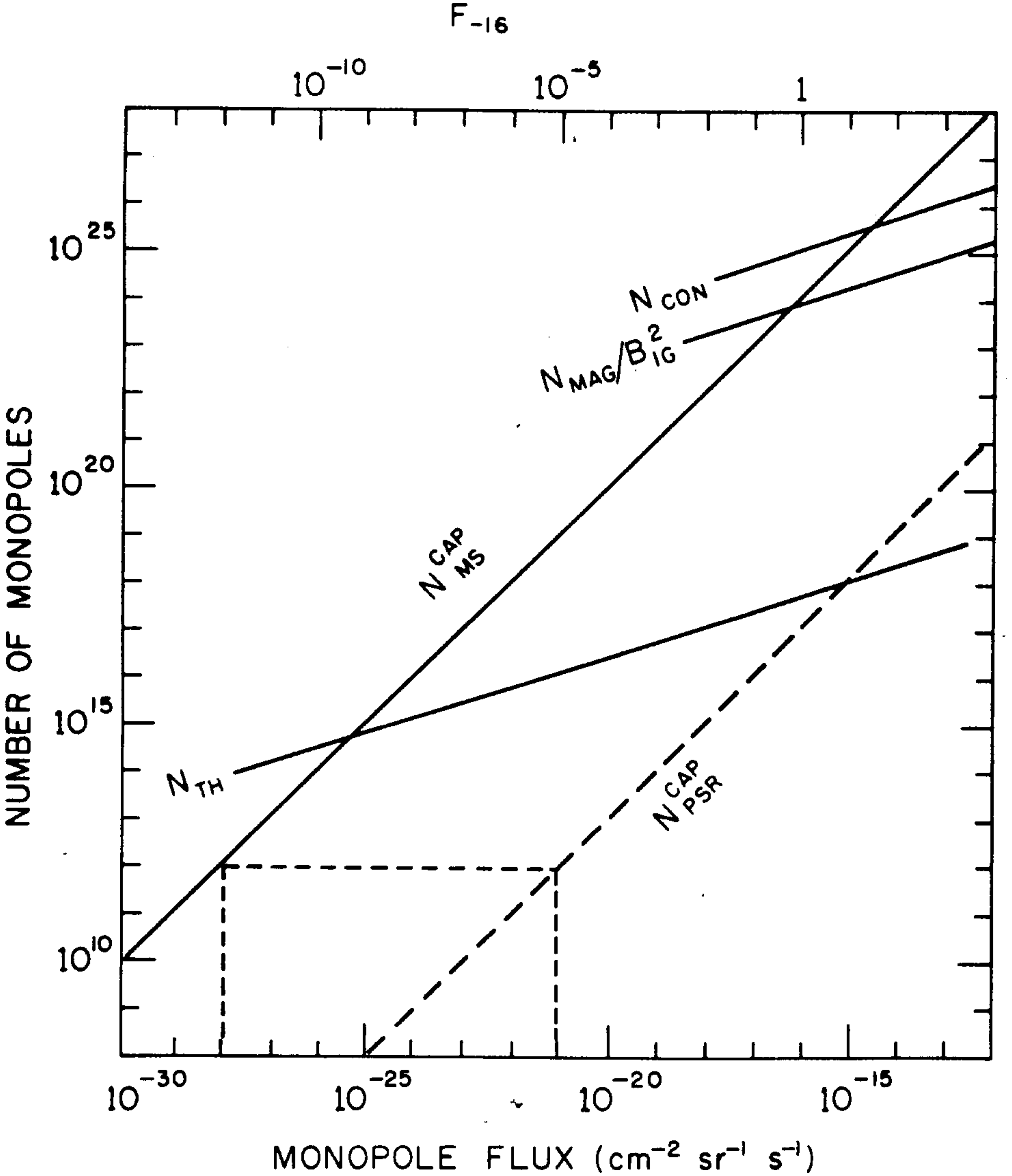
Fig. 3 - Number of monopoles captured by a $3M_\odot$ main sequence star in its lifetime (N_{MS}^{CAP}) and by a neutron star in 3×10^6 yrs (N_{PSR}^{CAP}). The effects of monopole-antimonopole annihilations in the main sequence star are shown--the equilibrium number of monopoles for the case that monopoles are supported against gravity by: (1) thermal velocity dispersion (N_{TH}); (2) magnetic field of 1 G (N_{MAG}/B_{1G}^2); (3) convective motions of the core (N_{CON}). For more details see ref. 34.


MONOPOLE FLUX BOUNDS (V=10^-3C)
MONOPOLE FLUX (CM^-2 SR^-1 S^-1)
MONOPOLE MASS (GeV)
10^-10
10^-15
10^-20
10^-25
10^-30
10^10
10^15
10^19
(UNIFORM)
MASS DENSITY
(CLUMPED)
PARKER
WD's
IC MAGNETIC FIELDS
MAGNETIC PLASMA OSCILLATIONS (ℓ = 1 KPC)
NEUTRON STARS
ΔB CATALYSIS
σ = 10^-28 cm^2
PSR 1929 + 10
WITH MS MM̄s
CABRERA
IONIZATION/ CATALYSIS SEARCHES
1 (FOOTBALL FIELD)^-1 YR^-1
1 (U of CHICAGO)^-1 YR^-1
1 CHICAGO^-1 YR^-1
1 IL^-1 YR^-1
1 EARTH^-1 YR^-1
1 SUN^-1 YR^-1

- FIG 1 -


10^{26}
10^{25}
10^{24}
10^{23}
N_M/F_{-16}
$g = g_D$, $\beta = 10^{-3}$
× 10^{15} GeV
○ 10^{16} GeV
□ 10^{17} GeV
0.3
1.0
10.
30.
$M/M_\odot$

-FIG 2-


F-16
10^-10
10^-5
1
NUMBER OF MONOPOLES
10^25
10^20
10^15
10^10
N CON
N MAG/B^2 IG
N CAP MS
N TH
N CAP PSR
10^-30
10^-25
10^-20
10^-15
MONOPOLE FLUX (cm^-2 sr^-1 s^-1)

- FIG 3 -

TABLE 1

SOURCES OF MONOPOLE AND DETECTOR MOTION

	MONOPOLE	DETECTOR
GRAVITATIONAL		
-Virgo Supercluster	2×10^{-3} c	2×10^{-3}c
-The galaxy	10^{-3} c	7×10^{-4}c
-Solar system	few $\times$ 10^{-4} c	10^{-4}c
-Earth	3×10^{-5} c	---
MAGNETIC		
-Galactic B-field	$3\times10^{-3}c(10^{16}GeV/m_M)^{1/2}$	
-Intragalactic B-field (upper limit)	$10^{-3}c(10^{16}GeV/m_M)$	

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