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Looking for the GUT Monopole

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Looking for the old Monopole *

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1. The GUT Monopole

Dirac pointed out 50 years ago that the existence of a magnetic monopole implies charge quantization (1). It is an amazing fact that charge quantization in unified gauge theories predicts magnetic monopoles (2). They are classical solutions of the equations of motion, with calculable mass. Conservation of magnetic charge makes them stable.

There is a heuristic argument for charge quantization (3). Put an e^+ in the field of an electromagnetic U(1) monopole of charge g . There is clearly an $\vec{r} \times \vec{E} \times \vec{B}$ contribution to the angular momentum, $\vec{J}^1 = -eg\vec{r}$. (\vec{r} points from monopole to charge.) Angular momentum is half integral, so the minimum monopole charge is $g = 1/2e$. Electric charges now come in units of e for the same reason.

What happens if we bring a d quark near the monopole? The result cannot depend on confinement, so set the inverse confinement radius to zero. (Now SU(3) color fields are of infinite range.) The U(1) contribution to the angular momentum is $\vec{J}^1 = +eg\vec{r}/3$. To get half integral total angular momentum we need $e.g.$ an extra $\vec{J}^2 = (+1/3)\vec{r}$. It comes from the product of the d color charge e_s and a nonzero color magnetic charge g_s . Consistency requires the monopole to have color and thus strong interactions.

This comes from unifying SU(3) x U(1) in a semisimple G. From now on, $G = SU(5)$.

A crude estimate of the monopole mass uses the magnetic field energy ignoring Z- γ mixing. Then $M \sim g^2/r_0$ where $r_0 \sim M_X^{-1}$. (The cutoff is there because Higgs and gauge fields vanish at $r = 0$.) Thus $M \sim M_X/3$; in SU(5) $M = 1 \times 10^{16}$ Gev = 1.8×10^{-8} gram (4). This is roughly the mass of a bacterium.

For $M \approx 10^{17}$ Gev the monopole has the Planck mass. If it survives quantum gravity effects it comes in its own black hole (a planckopole). Because the proton lifetime is $\sim M_X^2$, a light M can only appear in fairly radical unification

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schemes.

The large mass has consequences. Ambient monopoles will have $v \approx 30-3000$ km/sec or $\beta \approx 10^{-4}-10^{-2}$. The earth's gravitational potential is ~ 0.1 eV/Å. Even a small ($\Delta v \approx$ cm/sec) jolt will dislodge monopoles bound by atomic potentials $\sim 10^2$ eV. They then fall to the earths' core. As to asteroids, a modest bump ($\Delta v \approx 10^3$ cm/sec) will give any contained monopoles enough kinetic energy to escape against atomic binding forces, gravity and (for iron) conventional ohmic energy losses (5). Limits for light monopoles (6) need not apply for heavy ones.

GUT monopoles could have been made in the big bang long ago (and maybe by dying mini black hole bangs now) (7)(8). Perhaps the most reliable limit on the monopole to baryon ratio $n_M/n_B \approx 10^{-15}$ comes from present bounds on the universes' total mass density (8) $M_B \approx 10^{-15}$.

2. Conventional Searches via Ionization

Slow monopoles do not ionize much (5,9). To see this in a crude way, take the Fourier transform of the induced electric field on an atom due to a passing monopole, $\vec{E} \sim \dot{\vec{B}}$. At the frequency or energy to propel an electron into the continuum across an energy gap ≈ 1 eV, this Fourier transformed field is roughly proportional to $\exp(-b/\omega)$, where b is the impact parameter. Ionization vanishes rapidly below $\omega \approx 10^{-3}$ eV. (This naive estimate cannot be correct in detail; maybe the ionization is proportional to a high power of ω (10).)

There are other sources of ionization. Classically, direct monopole electron collisions transfer $< 2m_e^2 < 1$ eV for $\beta < 10^{-3}$. This is probably an ineffective source of ionization for $\beta < 10^{-4}$. Remarkably, the strong monopole magnetic field can shift atomic energy levels by $\Delta E \approx e g \hbar / a_0$ Ryberg in close collisions (11). In some materials the resulting level crossings could liberate excitations and eventually light (11).

My own naive and skeptical view is that ionization limits are credible for $\beta \geq 10^{-3}$ but that much theoretical work may be needed to make them so at $\beta < 10^{-4}$ (i.e. at typical solar system velocities).

Limits reported here are $\beta < .1 m^{-2} d^{-1} sr^{-1}$ (12) and $\beta < .014 m^{-2} d^{-1} sr^{-1}$ (13).
 D. Cline cites a limit around $2 \times 10^{-3} m^{-2} d^{-1} sr^{-1}$ for the Baksan detector in the USSR (14).

3. The Cabrera Candidate

Cabrera quotes a flux limit $F < F_c = .53 m^{-2} d^{-1} sr^{-1}$ with one candidate Dirac charge monopole, $g = 1/2e$ (15). This superconducting coil experiment is an elegant one with a clear signal and the candidate should be taken seriously. What does a flux $F \approx F_c$ imply? Firstly, conventional search limits indicate $\beta \approx 10^{-2}$ (i.e. less than typical stellar velocities). Estimates of the overall mass density of such monopoles are compatible with galactic mass estimates if $M \leq 10^{16}$ GeV and the monopoles are distributed as are stars and gas in our galaxy (15)(16).

Monopoles and antimonopoles eat galactic magnetic fields (17). The field energy density loss rate is $g \vec{v}_M \cdot \vec{B}$ and the field survival time becomes $\tau \approx \vec{B} / (8\pi g(4+F_c)) < 30$ yr. This fatally conflicts with the time needed to regenerate the field, of order the rotation period, $\approx 10^8$ yr. The $\vec{B} \approx 5 \times 10^{-6}$ gauss galactic field may eject monopoles with substantial velocity, $v \approx (2gBR/M)^{1/2} \approx 10^{-2} c$.

One cannot necessarily finesse this problem by making M larger ($\sim 10^{18}$ GeV) so that the monopoles are trapped by gravity, as then the total mass of monopoles at $F \approx F_c$ becomes $> 10^2$ the upper limit on the galactic mass. There is trouble.

(A startling alternative advocated by P. Eberhard (18) is that the galactic fields themselves are essentially due to plasma oscillations in a monopole-antimonopole gas. Parker's bound is then irrelevant. The oscillation period is $T = 2\pi / \omega_p = 2 \times 10^4$ yr. at $M = 1 \times 10^{16}$ GeV. One might expect fields disordered in magnitude and direction on scales larger than this. In particular, a collisionless $M = 7$ gas will not be flattened as is the visible galactic matter. This scenario may disagree with observations on the galactic fields and on the limits on $\beta = 10^{-3}$ monopoles. Nevertheless, it is quite interesting.)

A local solar system cloud of 5×10^{24} monopoles avoids these problems. (19) Cabrera's candidate gives a reasonable local density $n \approx 10^{-23} cm^{-3}$ with 5×10^{24} monopoles inside the earths' orbit and 5×10^{26} inside the sun (19). At $\beta \leq 10^{-2}$, ohmic losses in the sun are large enough so that fast passing monopoles stick in it after a collision. Accepting Parkers' limit from the survival of the galactic field, $v \approx 10^{-7} cm/yr$ (17), roughly the correct level of 5×10^{26} monopoles would be stuck in the sun after $\sim 10^9$ yr. They must be gradually and gently expelled so as to maintain the solar system cloud against a monopole diffusion loss time $\sim 10^8$ yr. How do the monopoles get out of the sun? The magnetic field expulsion velocity is of order 170 km/sec $(3L/Rc)^{1/2}$ where L is the field path length and B is in kilogauss. This is less than the escape velocity, ~ 300 km/sec - particularly since $L \approx 3_0$ and $B \approx$ kilogauss. The local cloud mechanism may only

neutron star contains 10^{15} (fm^2/s) $SO(3)$ monopoles. This is a stringent limit, since if $\rho_0 \sim \text{fm}^2/\text{s}$, $N \sim 10^{15}$.

Putting this another way, if the parent star's core had N' monopoles per solar mass and a fraction f end up in the neutron star, then $N \sim 10^{15} f (M_{\odot}/\text{fm}^2) M'$. Calculations of f and N' are in progress.

Let us accept $O(15, SO(3))$ monopoles per raw neutron star. Its magnetic field will be enormous. If nuclear matter is saturated, then the neutron star's luminosity increases linearly with N . For $N = 10^{15}$, $L \sim 10^{31}$ erg/s.

The above numbers have to be used with caution. They assume that ρ_0 is not very small. They ignore self-coupling of nuclear burning due to the intense energy flux, and also pion absorption. Nevertheless, we are now confronted with a Pac-Man model of the neutron star interior. It is amusing to recycle these considerations so as to get the energy generated by a fictitious monopole power reactor, $P \sim 10^5$ Na gigawatts, where N is the total number of monopoles and n the nucleon density per fm^3 . For $N = 1, n \sim 10^{15} \text{ fm}^{-3}$ we get a typical electric power plant output.

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work for monopoles of mass $M \sim 10^{15}$ GeV and even when its existence might be a local accident.

All this should perhaps remind us that even if a monopole is found it need not be the one expected in $SO(3)$.

4. The Rubakov Effect

Last year, V.A. Rubakov (20) discovered that unification monopoles induce nucleon decays, $N \rightarrow \pi + e + \nu$ or $\pi + e + \bar{\nu}$. Gaijin (21) has independently arrived at this same conclusion by a different argument. The $SO(3)$ matrix element is of the form $\langle N | \text{tr}(\bar{\psi}\psi) | N \rangle = C \rho^3$ where C is a constant independent of gauge couplings and M_X, M_Y . Thus the cross section can be of source interaction magnitude, measured in $(\text{fm})^2 = 10^{-26} \text{ cm}^2$ (26,27). The $SO(3)$ operator involved is like that for the conventional decay (apart from a factor $2/M_X^2$), so that induced nucleon decays will be hard to tell from spontaneous decay unless one sees several in a detector simultaneously, or detects the passage of a monopole. (Note that momentum transfers to or from the monopole should be small, $\sim m_p$. This is below the resolution of most detectors.)

We have no calculation of the cross section yet. Simple estimates will have to suffice. For a $\tau = 3 \text{ gm/cm}^2$ nucleon decay detector, the path length between induced decays caused by a traversing monopole is $\sim 50 \text{ cm}$ (fm^2/s). Using the Cabrera flux limit, $\sim 7 \times 10^3$ monopoles have passed thru e.g. SOUDAN I in 4 months. Hence $\tau < 3 \times 10^{-5} \text{ fm}^2$ or $\tau < 5 \text{ m}^2 \text{ sr}^{-1}$. Experimental limits should be quoted for τ or σ ($< 1.5 \times 10^{-5} \text{ fm}^2 \text{ m}^{-2} \text{ sr}^{-1}$ for SOUDAN I).

Because the universe expands rapidly during the big bang and because ρ_0/η is already large, the Rubakov effect does not destroy a significant fraction of the universes' baryon number (22). Neutron stars (23) are more interesting because $n \sim 1 \text{ fm}^{-3}$. Their magnetic fields accelerate monopoles to $v \sim (288R/M)^{1/2} \sim 1.8 \times 10^4 \text{ km/sec}$ for $B = 10^{12}$ gauss, $R = 10 \text{ km}$. Typical escape velocities are $\sim 5 \times 10^4 \text{ km/sec}$. So the fields can sweep up monopoles but cannot easily expell them against gravity. (This assumes $M = 1 \times 10^{16} \text{ GeV}$; much lighter monopoles would be both swept up and expelled.)

We write the cross section including the flux factor $\sigma = \sigma_0/\text{band}$ and estimate the luminosity of a neutron star from "nucleon burning" (24). Then with $n \sim 1/\text{fm}^3$ neutrons per unit volume we get a luminosity per $SO(3)$ monopole $L/N = \sigma n \cdot n$ (cm^2/fm^2) gram/sec/M. Luminosities are typically $L < 10^9 L_{\odot}$ and $L_{\odot} \sim 10^{33}$ gram/sec so we can find that $L/N \sim 10^{-13} L_{\odot} (\text{cm}^2/\text{fm}^2) n$ and a typical

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