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Looking for the GUT Monopole

by

T.F. Walsh

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I.F. Walsh

DESY, Hamburg

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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, $\vec{J}' = -eg\hat{r}$. ($\hat{r}$ 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 $\vec{J}' = + eg\hat{r}/3 = + 1/6\ \hat{r}$. To get half integral total angular momentum we need e.g. an extra $\vec{J}'' = (+ 1/3)\hat{r}$. It comes from the product of the d color charge e_s and a nonzero <u>color</u> 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 $M \sim g^2/r_o$ where $r_o \sim M_x^{-1}$. (The cutoff is there because Higgs and gauge fields vanish at r = 0.) Thus $M \sim M_x/\alpha$; in SU(5) $M = 1\times10^{16}$ GeV = 1.8×10^{-8} gram (4). This is roughly the mass of a bacterium.

For $M \gtrsim 10^{17}$ 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 $\tau_p \sim M_x^4$, a light M can only appear in fairly radical unification schemes.

The large mass has consequences. Ambient monopoles will have $v \gtrsim$ 30-3000 km/sec or $\beta \gtrsim 10^{-4}-10^{-2}$. The earth's gravitational potential is ~ 0.1 eV/Å. Even a small ($\Delta v \gtrsim$ cm/sec) jolt will dislodge monopoles bound by atomic potentials $\lesssim 10^{2}$ eV. They then fall to the earths' core. As to asteroids, a modest bump ($\Delta v \gtrsim 10^{3}$ 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 $n_M/n_B \lesssim 10^{-15}$ comes from present bounds on the universes' total mass density (8).

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, $\vec{E} \sim \beta \vec{B}$. At the frequency or energy to propel an electron into the continuum across an energy gap $\varepsilon \gtrsim 1$ eV, this Fourier transformed field is roughly proportional to $\exp(-b\,\varepsilon/v)$, where b is the impact parameter. Ionization vanishes rapidly below $v \sim b\varepsilon \sim a_0\varepsilon \sim 10^{-3}c$. (This naive estimate cannot be correct in detail; maybe the ionization is proportional to a high power of v (10).)

There are other sources of ionization. Classically, direct monopole electron collisions transfer $< 2m_e\beta^2 < 1$ eV for $\beta < 10^{-3}$. This is probably an ineffective source of ionization for $\beta \sim 10^{-4}$. Remarkably, the strong monopole magnetic field can shift atomic energy levels by $\Delta E \sim eg/a_0 \sim$ Rydberg in close collisions (9). In some materials the resulting level crossings could liberate exitations 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 $\beta \sim 10^{-4}$ (i.e. at typical solar system velocities).

Limits reported here are $F < .1 m^{-2}d^{-1}sr^{-1}$ (12) and $F < .014\ m^{-2}d^{-1}sr^{-1}$ (13). D. Cline cites a limit around $2 \times 10^{-5}\ m^{-2}d^{-1}sr^{-1}$ 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 $F \gtrsim F_c$ imply? Firstly, conventional search limits indicate $\beta < 10^{-3}$ (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 $\sim g n_M \vec{v}\cdot\vec{B}$ and the field survival time becomes $\tau \gtrsim \vec{B}/8\pi g(4\pi F_c) < 30$yr. This fatally conflicts with the time needed to regenerate the field, of order the rotation period, $\sim 10^{8}$ yr. The $\vec{B} \sim 5 \times 10^{-6}$ gauss galactic field may eject monopoles with substantial velocity, $v \sim (2gBR/M)^{1/2} \gtrsim 10^{-2}c$ (9).

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 $F \sim F_c$ 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-antimomopole gas. Parker's bound is then irrelevant. The oscillation period is $T = 2\pi/\omega_p = \gtrsim 2 \times 10^{4}$ 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 $M - \bar{M}$ 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 $\beta \lesssim 10^{-4}$ monopoles avoids these problems. (19) Cabreras' candidate gives a reasonable local density $n \gtrsim 10^{-23}\ cm^{-3}$ with $\gtrsim 10^{24}$ monopoles inside the earths' orbit and $\gtrsim 10^{26}$ inside the sun (19). At $\beta \lesssim 10^{-2}$, 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, $4\pi F < 10^{-7}\ cm^{-2}yr^{-1}$ (17), roughly the correct level of $\gtrsim 10^{26}$ 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 $(BL/R_\odot)^{1/2}$ where L is the field path length and B is in kilogauss. This is less than the escape velocity, $\gtrsim 300$ km/sec – particularly since $L \ll R_\odot$ and $B <$ kilogauss. The local cloud mechanism may only work for monopoles of mass $M \sim 10^{15}$ GeV and even then 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 SU(5).

4. The Rubakov Effect

Last year, V.A. Rubakov [20] discovered that unification monopoles catalyze nucleon decay, $N + X \to M + (e$ or $\mu) +$ mesons. (Callan [21] has independently arrived at this same conclusion by a different argument.) The SU(5) matrix element is of the form $\langle M\, u(r)u(r)d(r)e(r)\, M\rangle = C/r^6$ where C is a constant independent of gauge couplings and M_X, M_Y. Thus the cross section can be of strong interaction magnitude, measured in $(fm)^2 = 10^{-26}$ cm^2 [20,21]. The SU(5) operator involved is like that for the conventional decay (apart from a factor e^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, $\sim m_\mu$. 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 $\bar{\rho} = 3$ gm/cm^3 nucleon decay detector, the path length between induced decays caused by a traversing monopole is $\gtrsim 50$ cm (fm^2/σ). Using the Cabrera flux limit, $< 7 \times 10^3$ monopoles have passed thru e.g. SOUDAN I in 4 months. Hence $\sigma < 3 \times 10^{-5}$ fm^2 or $F <<$ .5$m^{-2}d^{-1}sr^{-1}$. Experimental limits should be quoted for τ_p or σF ($<1.5 \times 10^{-5}$ $fm^2 m^{-2} d^{-1} sr^{-1}$ for SOUDAN I).

Because the universe expands rapidly during the big bang and because n_γ / n_B 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 $n \sim 1$ fm^{-3}. Their magnetic fields accelerate monopoles to $v \sim (2gBR/M)^{1/2}$ $\sim 1.8 \times 10^4$ km/sec for $B = 10^{12}$ gauss, R = 10 km. Typical escape velocities are $\sim 5 \times 10^4$ km/sec. So the fields can sweep up monopoles but cannot easily expell them against gravity. (This assumes $M = 1 \times 10^{16}$ GeV; much lighter monopoles would be both swept up and expelled.)

We write the cross section including the flux factor $\sigma = \sigma_0/\beta$ and estimate the luminosity of a neutron star from "nucleon burning" [24]. Then with n ($\gtrsim 1/fm^3$) neutrons per unit volume we get a luminosity per SU(5) monopole $L/N = \sigma_0 n m_p \sim n\, (\sigma_0/fm^2)$ gram/sec/M. Luminosities are typically $L < 10^2 L_\odot$ and $L_\odot \gtrsim 10^{13}$ gram/sec so we can find that $L/N \sim 10^{-13} L_\odot (\sigma_0/fm^2) n$ and a typical

neutron star contains $\lesssim 10^{15}$ (fm^2/σ_0) SU(5) monopoles. This is a stringent limit, since if $\sigma_0 \sim fm^2$, $n_M/n_B \lesssim 10^{-42}$.

Putting this another way, if the parent star's core had N' monopoles per solar mass and a fraction ε end up in the neutron star, then $L \sim 10^{-13} \varepsilon (\sigma_0/fm^2) N'$. Calculations of ε and σ limit N'.

Let us accept $O(10^{15})$ SU(5) monopoles per new neutron star. Its' magnetic field may expel monopoles. If Parkers' bound is saturated, then the neutron stars' luminosity increases thereby by $\sim 10^{-3} - 10^{-2} L_\odot yr^{-1}$; old neutron stars may heat up.

The above numbers have to be used with caution. They assume that σ_0 is not very small. They ignore self-damping of nucleon 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, $P \gtrsim 10^5$ Nn gigawatts, where N is the total number of monopoles and n the nucleon density per fm^3. For N = 1, $n \sim 10^{-5}$ fm^{-3} we get a typical electric power plant output.

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