Monopole Catalysis of Nucleon Decay in Neutron Stars

Edward W. Kolb and Stirling A. Colgate
Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87544

and

Jeffrey A. Harvey
Physics Department, Princeton University, Princeton, New Jersey 08544
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From observed limits on the x-ray flux from neutron stars, a bound is placed on the product of the galactic flux of massive monopoles and the cross section for monopole-catalyzed nucleon decay: $F_M \sigma_{\Delta B} \lesssim 5\times 10^{-49}$ s^{-1} sr^{-1}.

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In a large class of grand unified theories, magnetic monopole solutions have been shown to exist.[1] It has also been shown that baryon number is not conserved in the presence of a monopole.[2,3] Recent model calculations[3] have led to the surprising result that the cross section for monopole-induced nucleon decay, e.g., $pM \to e^+\pi^0 M$, may be as large as a typical strong-interaction cross section: $\sigma_{\Delta B} \cong 10^{-27}$ cm^2. This result is potentially of great interest in light of the possible detection[4] of a monopole at a flux level of $F_M = 6\times 10^{-10}$ cm^{-2} s^{-1} sr^{-1}. In this paper, we find that limits on the luminosity of neutron stars imply that $F_M \sigma_{\Delta B} \lesssim 5\times 10^{-49}$ s^{-1} sr^{-1} which leads us to conclude that $\sigma_{\Delta B} \leq 4\times 10^{-39}$ cm^2 if the reported flux limit is representative of the galactic flux, or that $F_M \leq 5\times 10^{-22}$ cm^{-2} sr^{-1} s^{-1} if a strong cross section is representative for monopole-catalyzed nucleon decay.[5]

The basic point of the paper is that cosmic-ray monopoles hitting the neutron star will be trapped, and because of the high densities in the neutron star they will be efficient in catalyzing nucleon decay. By demanding that the energy produced by the monopole-induced decay be less than the observed discrete and background x-ray fluxes, we are able to limit the number of monopoles in the star, and hence limit the monopole flux integrated over the lifetime of the neutron star. Although the prediction and detection of young, cooling neutron stars is uncertain as a result of neutrino emission, nevertheless either the cumulative x-ray emission from the very many old neutron stars or the high probability of x-ray detection of nearby neutron stars imposes a significant upper limit on either the monopole density in the galaxy or the monopole-induced decay.

For our model of the neutron star we assume a mass of one solar mass (2×10^{33} g) at nuclear matter density ($\rho = 3\times 10^{14}$ g cm^{-3}), a radius of 10^6 cm, and a surface magnetic field of 10^{12} G. With the assumption of a monopole mass of 10^{16} GeV, on the surface of the neutron star the ratio of gravitational and magnetic forces is $\cong 70$. Since the B field falls at least as fast as R^{-3}, while the gravitational field falls as R^{-2}, as the monopole approaches the surface of the neutron star its interaction with the magnetic field can be neglected. If we ignore any monopoles present at the formation of the neutron star (including them will strengthen our limits), the number of monopoles that have been captured by the neutron star is given by

$$N_M = (2\pi/3) F_M A T, \tag{1}$$

where F_M is the monopole flux, T is the age of the neutron star, and A is the "effective" area of the neutron star. For an initial relativistic monopole, A is the actual area of the neutron-star surface. However, for the massive monopoles considered here, one expects the monopoles (and the neutron stars) to have velocity distributions typical either of the virial velocity of the galaxy ($v \cong 10^{-3}c$) or of heating by the magnetic field of the galaxy[6] ($v \cong 3\times 10^{-3}c$). The magnetic field acceleration of monopoles leads to a mass-dependent velocity $3\times 10^{-3}c[M_M/(10^{16}\text{ GeV})]^{-1/2}$ in a coherence length of 300 parsecs (pc). Since the magnetic field is expected to be time dependent on a time scale similar to that of the monopole, we expect the galactic monopoles to be heated and ejected with close to their virial velocity. Recognizing a factor of 3 uncertainty in the velocity, we chose the virial velocity as representative of monopoles trapped in the galaxy. The monopoles can be captured if their orbit intersects the surface of the neutron star.[7] The equations of motion relate the capture radius and the radius of the neutron star:

$$\left(\frac{R_{\rm capture}}{R_{\rm NS}}\right)^2 = \frac{1+2M_{\rm NS}G/v_M{}^2R_{\rm NS}}{1-R_{\rm S}/R_{\rm NS}} \cong 4.2\times10^5 \quad (v_M=10^{-3}c). \tag{2}$$

In Eq. (2), the subscript NS refers to the neutron star, the subscript M refers to the monopole, $R_{\rm S}$ is the Schwarzschild radius, and the $R_{\rm S}/R_{\rm NS}$ term represents the post-Newtonian correction.

Each nucleon decay releases about a nucleon rest mass of energy in the form of muons, pions, photons, etc. The specific luminosity due to monopole-induced nucleon decay is[8]

$$L_M = m_N n_N \sigma_{\Delta B}|v| \cong 8.5\times10^{44}\sigma/(1\ {\rm cm}^2)\ {\rm ergs\ s}^{-1}\ {\rm monopole}^{-1}, \tag{3}$$

where n_N and m_N are the nucleon density and mass, and $|v|$ is the relative velocity between the monopole and the nucleon [we have assumed $|v|=10^{-1}c$ in Eq. (3)]. We parametrize the cross section as

$$\sigma=\pi/\Lambda^2=10^{-27}\Lambda_{\rm GeV}{}^{-2}\ {\rm cm}^2, \tag{4}$$

where $\Lambda_{\rm GeV}=\Lambda/(1\ {\rm GeV})$. If the monopole-induced nucleon decay is characterized by a strong cross section, then $\Lambda_{\rm GeV}$ should be of order unity.

Combining Eqs. (2)–(4), we obtain the luminosity:

$$L=2.0\times10^{54}\Lambda_{\rm GeV}{}^{-2}F_M/(1\ {\rm cm}^{-2}\ {\rm s}^{-1}\ {\rm sr}^{-1})\ {\rm ergs\ s}^{-1}, \tag{5}$$

where we have used 10^{10} yr as the age of the neutron star on the basis that massive star formation and evolution occurred early after the formation of the galaxy.

A limit on the photon luminosity of old neutron stars comes from the isotropic background limit for the total x-ray emission per neutron star,[9]

$$P(>0.2\ {\rm keV}) \lesssim 6\times10^{49}\ {\rm ergs}, \tag{6}$$

under the assumption of a production rate of one neutron star per century. If we assume a time scale of 10^{10} yr of a typical neutron star, then Eq. (6) implies an x-ray luminosity limit of $L_{\rm iso}{}^\gamma \lesssim 2\times10^{32}$ ergs s^{-1}. Recent surveys for serendipitous x-ray sources are able to see discrete sources with an x-ray luminosity of $L_{\rm dis}{}^\gamma=10^{31}$ ergs s^{-1} at a distance of 1 kpc.[10] On the basis of the current estimated birth rate of pulsars in the solar neighborhood, the number density of old neutron stars is expected to be at least $n_{\rm NS}\gtrsim 4\times10^{-3}$ pc^{-3}, with some estimates higher by more than an order of magnitude.[11] Therefore, the dearth of sources in the surveys can only be explained if the x-ray luminosity of old neutron stars is less than $L_{\rm dis}{}^\gamma$.

The luminosity due to monopole-catalyzed nucleon decay given by Eq. (5) would, in general, be emitted as both photons and neutrinos. In the absence of a pion condensation or free quarks, the luminosity is dominated by photons for total luminosities less than 10^{33} ergs s^{-1}, and the limits $L\leqslant L_{\rm iso}{}^\gamma$ and $L\leqslant L_{\rm dis}{}^\gamma$ may be used.[12] However, if pions condense in the interior of neutron stars or free quarks exist, neutrino emission is enhanced, and a photon luminosity of 10^{31} ergs s^{-1} (2×10^{32} ergs s^{-1}) corresponds to a *total* neutrino-plus-photon luminosity of 10^{33} ergs s^{-1} (10^{36} ergs s^{-1}).[12,13] Therefore the limits on the x-ray luminosity translate into limits on the total luminosity of $L\leqslant10^{33}$ ergs s^{-1} ($L^\gamma\leqslant L_{\rm dis}{}^\gamma$), and $L\leqslant10^{36}$ ergs s^{-1} ($L^\gamma\leqslant L_{\rm iso}{}^\gamma$). The limits on the total luminosity constrain the product of the monopole flux and the monopole-catalyzed nucleon decay cross section:

$$\begin{aligned}[\Lambda/(1\ {\rm GeV})]^{-2}F_M/(1\ {\rm cm}^{-2}\ {\rm s}^{-1}\ {\rm sr}^{-1}) &\leqslant 5\times10^{-19}\quad (L^\gamma\leqslant L_{\rm iso}{}^\gamma),\\ &\leqslant 5\times10^{-22}\quad (L^\gamma\leqslant L_{\rm dis}{}^\gamma).\end{aligned} \tag{7}$$

If we assume that $\Lambda_{\rm GeV}=1$, the flux limit $F_M\lesssim5\times10^{-22}$ cm^{-2} s^{-1} sr^{-1} is much lower than any previous limit[6] and is *twelve* orders of magnitude smaller than detection at the reported limit,[4] and represents a galactic monopole density of $n_M\lesssim 2\times10^{-29}$ cm^{-3} under the assumption of an average monopole velocity of $10^{-3}c$. A density this low means that in our galaxy the "monopole number" $M\equiv n_M/n_\gamma=n_{\bar M}/n_\gamma$ is less than 4×10^{-32}. It is uncertain whether the galaxy represents a local monopole enhancement or rarefaction due to the competing effects of gravitation and magnetic field heating. Regardless, the limit on M prevents the monopoles from being the dark matter in the universe. If we assume that the flux reported by Cabrera is correct, then $\sigma_{\Delta B}<10^{-39}$ cm^2 ($\Lambda>6\times10^5$ GeV), and the magnitude for monopole-catalyzed neutron decay is much different than the model calculations suggest. In either case, monopole-induced proton decay should not be detectable in proton-decay experiments.

Of course saturation of the limits of Eq. (7) leads to the interesting result that old neutron stars are hotter than young neutron stars, and that a significant fraction of the x-ray flux is caused by monopole-induced nucleon decay in neutron stars.

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After submission of this paper we learned that Dimopoulos, Preskill, and Wilczek have also considered monopole catalysis of nucleon decay in neutron stars[14] and have reached similar conclusions.

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[5]Previous searches for *ionizing* monopoles have resulted in a flux limit of $F \lesssim 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. See, e.g., P. B. Price, E. K. Shick, W. L. Osborne, and L. S. Pinsky, Phys. Rev. Lett. 35, 487 (1975); K. Kinoshita and P. B. Price, Phys. Rev. D 24, 1707 (1981).

[6]M. S. Turner, E. N. Parker, and T. J. Bogdan, to be published, have reexamined the limit inferred by the galactic magnetic field [E. N. Parker, Astrophys. J. 163, 225 (1971)] and confirm the previous result $F \lesssim 10^{-16}$ cm^{-2} sr^{-1} cm^{-1} for 10^{16}-GeV mass monopoles, and a larger flux limit for more massive ones.

[7]When the monopole strikes the neutron star surface it will be semirelativistic ($v \cong c/3$). In relativistically degenerate matter, ordinary ionization loss is severly reduced. Interactions are limited to the Fermi surface and effectively to those electrons whose parallel component of velocity is $\pm c/3$ from that of the monopole, or a volume of order E_F^{-2} or a fraction of electrons $\cong 10^{-2}\rho_6^{-2/3}$. Monopoles initially of virial velocity would be stopped in the deep surface layers $\rho \cong 10^{12}$ g cm^{-3}, but the small energy loss required to transform a hyperbolic surface grazing orbit to a bound one would take place in much less matter. Nucleon-monopole scattering ensures capture of even highly relativistic monopoles within the core matter.

[8]We assume that the catalysis of nucleon decay is a statistically independent process. If the average separation of nucleons is less than $\Lambda_{\rm GeV}^{-1}$ this approximation may break down. However, in this case the heating rate should be higher than given by Eq. (3).

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