Monopole Catalysis of Nucleon Decay in Old Pulsars

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The *measured* x-ray fluxes of old, nearby pulsars are used to constrain the monopole flux times the cross section for monopole-catalyzed nucleon decay. Observations of PSR 1929+10 provide the best limit: $F\times\sigma v/(3\times10^{-18}\ \mathrm{cm}^3\ \mathrm{s}^{-1}) \leq 7\times10^{-22}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$. When the monopoles captured by the progenitor star while it was on the main sequence are taken into account, the limit becomes $F\times\sigma v/(3\times10^{-18}\ \mathrm{cm}^3\ \mathrm{s}^{-1})\leq 2\times10^{-28}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$.

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Rubakov[1] and Callan[2] made the remarkable discovery that the monopoles predicted in a large class of grand unified theories[3] should catalyze nucleon decay[4] (e.g., $M+p\rightarrow M+\pi^0+e^+$) with a cross section comparable to "typical strong-interaction cross sections." Several authors[5-8] have used this fact to obtain stringent bounds on the product of the monopole flux and the cross section for catalysis. The basic idea is that an object (e.g., neutron star, white dwarf, Earth, Jupiter, etc.) stops some (or all) of the monopoles incident upon it; once captured, these monopoles catalyze nucleon decays within the object, thereby releasing energy; this results in a flux of photons from the surface of the object. Observational limits to the photon flux can then be used to constrain the incident flux of monopoles. Consideration of the catalysis process in neutron stars results in the most stringent limit to the monopole flux.[5-7] In addition, the uncertainties in the catalysis process due to strong-interaction physics, etc.,[9] should be unimportant in neutron stars since monopole-nucleon relative velocities are large ($\simeq 0.3c$).

Previous monopole flux limits based upon monopole-catalyzed nucleon decay in neutron stars were obtained in two different ways: (1) As a result of monopole-catalyzed nucleon decay neutron stars will be x-ray sources. Assuming a number density ($n\geq 4\times10^{-3}\ \mathrm{pc}^{-3}$) (pc denotes parsec) of old ($\simeq 10^{10}$ yr) neutron stars Kolb, Colgate, and Harvey[5] used the negative results of Einstein Observatory serendipitous searches for discrete x-ray sources to derive the limit $F\lesssim 5\times10^{-22}[\sigma v/(3\times10^{-18}\ \mathrm{cm}^3\ \mathrm{s}^{-1})]^{-1}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$, where σv is the cross section for catalysis times the relative velocity of the monopole and nucleon. (2) The photons emitted (x rays of energy ≈ 100 eV) by neutron stars as a result of the catalysis process contribute to the diffuse x-ray background. *Assuming* a number density of old neutron stars similar to that in (1), Dimopoulos, Preskill, and Wilczek[6] used the measured diffuse x-ray background flux to obtain $F\lesssim 10^{-25}[\sigma v/(3\times10^{-18}\ \mathrm{cm}^3\,\mathrm{s}^{-1})]^{-1}\mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$. These limits are extremely stringent (many orders of magnitude more restrictive than the Parker bound[10] $\simeq 10^{-16}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$, or the flux inferred from Cabrera's candidate event[11] $\simeq 10^{-10}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$), and thus are very important guide posts for "monopole hunters."

Because of their significance, these limits must be subjected to great scrutiny. At present they involve several apparent weaknesses. First, both limits (1) and (2) rely on an assumed number density of old neutron stars which appears to be too high. The birth rate of pulsars (the largest *known* contribution to the neutron-star birth rate) indicates a local number density of about a factor of 40 lower[12] ($\simeq 10^{-4}\ \mathrm{pc}^{-3}$). Second, interstellar absorption of the x rays emitted by the neutron stars reduces their apparent luminosity, and has been neglected in both Refs. 5 and 6. Absorption is very significant since the absorption length is $l_{\mathrm{abs}}\simeq(6\ \mathrm{pc})[E/(100\ \mathrm{eV})]^3[n_{\mathrm{H}}/(1\ \mathrm{cm}^{-3})]^{-1}$, where n_{H} is the average number density of hydrogen atoms along the line of sight. When both of these effects are taken into account,[12] limit (2) becomes about six orders of magnitude *less* stringent, $F\lesssim 10^{-19}[\sigma v/(3\times10^{-18}\ \mathrm{cm}^3\ \mathrm{s}^{-1})]^{-1}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$. Limit (1), which is based upon serendipitous searches, depends crucially on the number of potential sources *expected* in the volume surveyed. Using $n\simeq 10^{-4}\ \mathrm{pc}^{-3}$ and assuming that only sources closer than 100 pc can be detected (because of interstellar absorption), we find that the number of sources expected is $N_s\simeq 10^{-2}[d\Omega/(1\ \mathrm{deg}^2)]$. Since the serendipitous survey cited in Kolb, Colgate, and Harvey[5] only covered $\approx 10\ \mathrm{deg}^2$, one would expect to find less than one source. Olive and Schramm[13] have pointed out a third weakness: A flux of $\simeq 10^{-14}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$ cannot be precluded by arguments (1) or (2). Such a flux would cause neutron stars to evaporate in a time $\simeq 10^8$ yr, thereby drastically reducing the number density of old neutron stars.

In this Letter we derive a flux bound which is based upon the *observed* x-ray luminosities of nearby ($d \lesssim 500$ pc), old ($\gtrsim 10^6$ yr) radio pulsars, and which is numerically similar to the most stringent bound of Kolb, Colgate, and Harvey.[5] In obtaining this bound, we only consider the monopoles captured by the pulsar since its birth ($\simeq 10^6$ yr ago). If we also take into account monopoles captured by the progenitor main-sequence (MS) star, then the flux bound becomes about six orders of magnitude more stringent.

Throughout we shall display the dependence of all quantities upon the values of the various parameters we use. Following Rubakov,[1] we take the cross section for catalyzed nucleon decay times relative velocity to be constant: $(\sigma v) = (\sigma v)_{-28} \times (10^{-28}\ \mathrm{cm}^2) \times (3 \times 10^{10}\ \mathrm{cm\ s^{-1}})$. For our model of a neutron star we use[14] $M = M_{1.4} \times 1.4 M_\odot$, $R = R_{15} \times (15\ \mathrm{km})$, and $\bar{\rho} = M/(4\pi R^3/3) = (2.0 \times 10^{14}\ \mathrm{g\ cm^{-3}}) M_{1.4} R_{15}^{-3}$. (Note that for degenerate neutron matter R and M are related by $R_{15} = M_{1.4}^{-1/3}$.) Since most of the monopoles captured by a neutron star sink to the center, the central density is most relevant; in neutron-star models[14] it is typically of the order of a factor of 3 times the average density, and so we write $\rho_c = 3 f \bar{\rho}$

Monopoles less massive than about 10^{21} GeV moving with velocities of order $10^{-3}c$ will lose sufficient energy passing through a neutron star to be captured.[5,6] The number of monopoles captured by a neutron star exposed to a monopole flux $F = F_{-16} \times 10^{-16}\ \mathrm{cm^{-2}\ sr^{-1}\ s^{-1}}$ for a time $\tau = \tau_6 \times 10^6$ yr is (for $m_M \lesssim 10^{21}$ GeV) just the number of monopoles incident upon the star,

$$N_M \simeq (4\pi R^2)(\pi\ \mathrm{sr})[1 + (v_{\mathrm{esc}}/v_M)^2] F\tau, \tag{1a}$$

$$\simeq 8\pi^2 (GMR/v_M{}^2) F\tau \simeq 7.8 \times 10^{16} a_2 F_{-16}, \tag{1b}$$

where $a_2 = \tau_6 R_{15} M_{1.4} \beta_{-3}{}^{-2}$, the monopole's velocity far from the star is $v_M = \beta_{-3} \times 10^{-3} c$, and v_{esc} is the escape velocity from the surface of the neutron star. The factor $1 + (v_{\mathrm{esc}}/v_M)^2 \simeq 2GM/Rv_M{}^2$ is just the ratio of the capture area to the geometric cross section. Monopoles in the galaxy will, on average, be moving with at least the virial velocity ($\simeq 10^{-3}c$), and faster if they have been accelerated by the galactic field[15]: $v_M \simeq 3 \times 10^{-3} c (10^{16}\ \mathrm{GeV}/m_M)^{1/2}$ (for field strength $\simeq 3 \times 10^{-6}$ G and coherence length $\simeq 300$ pc).

The luminosity due to monopole-catalyzed nucleon decay (per monopole) is

$$L_1 = \rho_c c^2 (\sigma v) \simeq 1.6 \times 10^{18} a_1\ \mathrm{erg\ s^{-1}}, \tag{2}$$

where $a_1 = (\sigma v)_{-28} R_{15}{}^{-3} M_{1.4} f$. The total luminosity of a neutron star due to monopole-catalyzed nucleon decays is then just

$$L_{\mathrm{tot}} \simeq N_M L_1 \simeq 1.3 \times 10^{35} a_3 F_{-16}\ \mathrm{erg\ s^{-1}}, \tag{3}$$

where $a_3 = \tau_6 R_{15}{}^{-2} M_{1.4}{}^2 (\sigma v)_{-28} \beta_{-3}{}^{-2} f$.

Next we compare this luminosity to the *measured* luminosities of old radio pulsars.[16] Helfand and his collaborators[17] have used the Einstein Observatory to study x-ray emission from more than ten old (spin-down ages $5 \times 10^5 - 10^7$ yr,[18] nearby ($d \lesssim 500$ pc) radio pulsars (including PSR's 0031-07, 0355+54, 0655+64, 0809+74, 0950+08, 1055-52, 1133+16, 1508+55, 1642-03, 1929+10, and 1952+29), and have inferred temperatures (and in some cases just upper limits) of between 2×10^5 and 5×10^5 K. For our purposes the most favorable object is PSR 1929+10, a very nearby ($d \simeq 60$ pc)[19] radio pulsar, with the lowest detected surface temperature ($\simeq 2 \times 10^5$ K), and a spin-down age of 3.1×10^6 yr. Corrected for interstellar absorption, the x-ray luminosity of this object in the 0.2–4 keV energy range is $6 \times 10^{28}\ \mathrm{erg\ s^{-1}}$. This translates into a surface temperature of 2×10^5 K and total photon luminosity of $2.6 \times 10^{30} R_{15}{}^2\ \mathrm{erg\ s^{-1}}$. At this photon luminosity the neutrino luminosity should not be significant[20] (even for quark matter or pion condensate equations of state), so that $2.6 \times 10^{30} R_{15}{}^2$ erg s^{-1} can be taken as the total luminosity of PSR 1929+10.

Using this measurement and Eqs. (1)–(3) we obtain limits to the number of monopoles in PSR 1929+10 and to the monopole flux:

$$N_M \lesssim 1.6 \times 10^{12} (\sigma v)_{-28}{}^{-1} f^{-1} R_{15}{}^5 M_{1.4}{}^{-1}, \tag{4a}$$

$$F \lesssim 6.7 \times 10^{-22} a_4\ \mathrm{cm^{-2}\ sr^{-1}\ s^{-1}}, \tag{4b}$$

where $a_4 = (\tau_6/3)^{-1} (\sigma v)_{-28}{}^{-1} R_{15}{}^4 \beta_{-3}{}^2 M_{1.4}{}^{-2} f^{-1}$. This is our main result.[21,22]

The progenitor stars which gave birth to PSR 1929+10 (and other nearby, old radio pulsars) should have captured monopoles while they were on the MS. The number captured depends upon the energy-loss rate and the radius, mass, and MS lifetime of the star (R, M, and τ_{MS}). Using the energy-loss rates of Tarlé and Ahlen[23] for a monopole passing through a nondegenerate electron gas, Freese, Frieman, and Turner[24] find that MS stars in the range $(1-20)M_\odot$ can stop a significant fraction of the monopoles moving with speeds $\lesssim(3-5)\times10^{-3}c(10^{16}\ \mathrm{GeV}/m_M)^{1/2}$ which strike them. For a $10M_\odot$ star (stars of about this mass are thought to be the progenitors of neutron stars; $R\simeq3.6R_\odot$ and $\tau_{\rm MS}\simeq40\times10^6$ yr) the number of 10^{16}-GeV monopoles moving with speed $10^{-3}c$ captured on the MS is[24] $\simeq10^{24}F_{-16}$ (this number scales approximately as M^{-2}). Comparing this number to the limit on N_M obtained from PSR 1929+10, we obtain the much more stringent, but less secure bound,[25]

$$F\lesssim2\times10^{-28}a_5\ \mathrm{cm^{-2}\ sr^{-1}\ s^{-1}}, \tag{5}$$

where $a_5=(\sigma v)_{-28}{}^{-1}f^{-1}R_{15}{}^5M_{1.4}{}^{-1}$.

Finally, consider the possible effect of monopole-antimonopole annihilations on the limits discussed above [Eqs. (4b) and (5)]. It is generally believed that the interiors of neutron stars are superconducting.[14] In this case, monopoles will be confined to flux tubes and as long as the number of flux tubes ($\simeq10^{31}B_{12}$; magnetic field strength $B\simeq B_{12}\times10^{12}$ G) exceeds the number of monopoles annihilations will not be important[26]—for the limits discussed here this requirement is clearly satisfied. In the unlikely case that neutron star interiors are not superconducting, and the fields are too weak to separate monopoles and antimonopoles ($\ll10^8$ G, see Ref. 26), monopole-antimonopole annihilations may be significant. The equilibrium abundance is determined by balancing the incoming monopole flux with the rate of annihilations. Harvey[26] finds that the equilibrium abundance $N_{\rm eq}\simeq1.6\times10^{15}(F_{-16}M_{1.4}R_{15}\beta_{-3}{}^{-2})^{1/2}$. For PSR 1929+10 the constraint on N_M from x-ray observations [cf. Eq. (4a)] implies that the number of monopoles captured since the pulsar's birth could not have attained the equilibrium abundance, and thus annihilations do not affect our bound (4b). If, in addition, we include the monopoles captured by its MS progenitor, then the number of monopoles can easily reach $N_{\rm eq}$, and our bound (5) becomes

$$F\lesssim1.0\times10^{-22}a_6\ \mathrm{cm^{-2}\ sr^{-1}\ s^{-1}} \tag{6}$$

when annihilations are taken into account, where $a_6=(\sigma v)_{-28}{}^{-2}f^{\ 2}R_{15}{}^9M_{1.4}{}^{-3}\beta_{-3}{}^2$.

In conclusion, we have used x-ray observations of old radio pulsars to derive a very stringent bound on the average galactic flux of monopoles over the past 10^6 yr: $F\lesssim6.7\times10^{-22}\,a_4\ \mathrm{cm^{-2}\ sr^{-1}\ s^{-1}}$. While numerically similar to previous bounds[5-7] based on catalyzed-nucleon decay in neutron stars, this bound appears to be more reliable. When the monopoles captured by the MS progenitor are also taken into account, our bound improves by about six orders of magnitude.

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[21]The bounds derived from observations of the other nearby pulsars mentioned in the text are less restrictive by factors ranging from 5 to 30.

[22]Since $T \simeq 2 \times 10^5$ K $\simeq 18$ eV and the Einstein Observatory detector threshold is ≈ 200 eV, only about $\frac{1}{40}$ of the incident energy flux from PSR 1929+10 is detected. If the radiating surface area of the pulsar is smaller than we assumed (e.g., $R < 15$ km, or if the radiation is emitted primarily from the magnetic polar caps), then for a given total photon luminosity the temperature must be higher and the detection efficiency (exponentially) better. If this is the case, the resulting flux bounds are more stringent (up to a factor of 40 for PSR 1929+10). This possibility is *not* accounted for in our simple scaling factor a_4.

[23]G. Tarlé and S. P. Ahlen, to be published.

[24]K. Freese, J. Frieman, and M. S. Turner, to be published.

[25]When taking into account the monopoles captured on the MS, one must worry about what happens to the monopoles during neutron star formation. This is discussed in more detail in Ref. 24 and J. Harvey and J. Shaham, to be published; here we briefly summarize their conclusions. The biggest worry is annihilations as the interior of the nuetron star goes superconducting. If, as is most likely, the superconductivity works its way from the center of the star outward, then annihilations are insignificant. In the less likely case that it proceeds from the outside inward, it is argued that *at least* one monopole survives per magnetic flux tube in the volume occupied by the monopoles ($r_M \simeq 10^{-2}$ cm), which is $\simeq 3 \times 10^{15} B/(10^{12}$ G) monopoles. Since this is greater than the bound on the number of monopoles in PSR 1929+10, our constraint (5) is not affected even in this "worst case" scenario.

[26]J. Harvey, to be published.