TeV $\mu$ Neutrinos from Young Neutron Stars

Bennett Link
Montana State University, Department of Physics, Bozeman MT 59717, USA

Fiorella Burgio
INFN Sezione di Catania, Via S. Sofia 64, I-95123 Catania, Italy

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Neutron stars are efficient accelerators for bringing charges up to relativistic energies. We show that if positive ions are accelerated to $\sim 1$ PeV near the surface of a young neutron star ($t_{\text{age}} \lesssim 10^5$ yr), protons interacting with the star’s radiation field will produce beamed $\mu$ neutrinos with energies of $\sim 50$ TeV that could produce the brightest neutrino sources at these energies yet proposed. These neutrinos would be coincident with the radio beam, so that if the star is detected as a radio pulsar, the neutrino beam will sweep the Earth; the star would be a “neutrino pulsar”. Looking for $\nu_\mu$ emission from young neutron stars will provide a valuable probe of the energetics of the neutron star magnetosphere.

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Pulsar emission is interpreted as a consequence of the acceleration of charges to relativistic energies somewhere in the neutron star’s magnetosphere. As the charges (positive ions or electrons) move along the curved magnetic field lines, they produce curvature radiation which in turn produces a pair cascade and beamed radiation (see [1] for a review). A long-standing and unsolved problem in neutron star magnetospheric physics is where charges obtain most of their energy. Near the stellar surface, charges are constrained to move along magnetic field lines. In the presence of the plasma, the field lines are approximate equipotentials; the electric and magnetic fields satisfy $\mathbf{E} \cdot \mathbf{B} \approx 0$ for a quasistatic magnetosphere. In most theories of pulsar emission, charge acceleration occurs in a charge depleted polar region very near the stellar surface, sustained by a deviation of the magnetosphere from corotation with the star [2, 3, 4]. An alternative is the “outer gap” model [5] in which the acceleration site can be far from the stellar surface. To determine exactly where and how the charges are accelerated would require a detailed description of the neutron star magnetosphere, which we currently lack. Here we show that young neutron stars might be among the brightest sources of muon neutrinos yet proposed, and so might be the first sources to be detected by planned or operating neutrino telescopes such as AMANDA-II and IceCube [6], and ANTARES, NEMO and NESTOR [7]. The detection of young neutron stars as strong neutrino sources would be a fascinating breakthrough in its own right, and would indicate that protons (or heavier ions) are accelerated to high energies close to the star, thus providing an important probe of the energetics and physical conditions that prevail in the poorly understood magnetosphere of a neutron star.

If the star’s magnetic moment $\mu$ and angular velocity $\Omega$ satisfy $\mu \cdot \Omega < 0$ (as one would expect for half of neutron stars), positive ions will be accelerated to infinity. If the neutron star is young, its surface will emit brightly in soft x-rays, and the protons in accelerated nuclei will scatter with this radiation field. If the protons are sufficiently energetic, they will exceed the threshold for photomeson production through the $\Delta$ resonance (the $\Delta^+$ is an excited state of the proton, with a mass of 1232 MeV). The $\Delta^+$ quickly decays to a $\pi^+$, and muon neutrinos are produced through the following channels:

$$p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+ \rightarrow n\nu_\mu \mu^+ \rightarrow ne^+ \nu_e \nu_\mu \nu_\mu. \quad (1)$$

This idea for $\nu_\mu$ production was explored by [8] in the context of magnetars. In this paper we explore a similar idea in a different physical regime, that of young, hot neutron stars. We show that young neutron stars could be strong sources of muon neutrinos, with energies $\sim 50$ TeV, and with fluxes observable by large-area neutrino observatories.

**Energetics.** Goldreich & Julian [8] showed that the potential drop across the field lines of a pulsar from the magnetic pole to the last field line that opens to infinity is of magnitude $\Delta \Phi = \mu \Omega^2 / 2c^2$, where $\mu = BR^3$ is the stellar magnetic moment, $B$ is the strength of the dipole component of the field at the magnetic poles and $R$ is the stellar radius. If charges in rapidly rotating pulsars with unexceptional fields ($B \sim 10^{12} \text{ G}$) could be accelerated by this potential drop, the corresponding energy would be huge (neglecting radiation losses, but see below)

$$\epsilon_\Phi = eZ\Delta \Phi = 7ZB_{12}p_{\text{ms}}^{-2} \text{ EeV}, \quad (2)$$

per ion, where $e$ is the electronic charge, $Z$ is the charge number of the ion, $B_{12} \equiv B/10^{12}$, $p_{\text{ms}}$ is the spin period in milliseconds and $R \sim 10^6 \text{ cm}$ is the stellar radius. Near the star, charges are constrained to follow the magnetic field lines. For a charge to be accelerated, $\mathbf{E} \cdot \mathbf{B} \neq 0$ is required. Moreover, there must at least some acceleration near the stellar surface, to supply the charges
that support the magnetosphere. As a conjecture to be tested by neutrino observations, we shall assume that a strong, accelerating field exists near the stellar surface. In this case, radiation losses will determine whether or not nuclei can attain energies of the magnitude given by eq. [2]. The power dissipated by a charge $q$ of energy $\epsilon$ moving along a field line of radius of curvature $\rho_0$ is $\frac{d\epsilon}{dt} = \frac{2}{3}(q^2 c/\rho_0^2)(\epsilon/mc^2)^4$. The acceleration time scale is $\sim \rho_0/c$, giving $d\epsilon/dt \approx \epsilon/c/\rho_0$. Near a pole of a magnetic dipole, $\rho_0 \gtrsim R$. Radiation losses limit the acceleration per nucleon of a nucleus of mass number $A$ to be $\epsilon_{\text{max}} \sim 20(A/Z^2)^{1/3}$ PeV. Hereafter we assume $Z/A \approx 1/2$.

Now we estimate the photomeson production threshold to compare with the radiation loss limit. The threshold condition for a proton to reach the $\Delta$ resonance is that the proton and photon energies, $\epsilon_p$ and $\epsilon_\gamma$, respectively, satisfy

$$\epsilon_p \epsilon_\gamma \geq 0.3 \text{ GeV}^2 f_g, \quad f_g \equiv (1 - \cos \theta_{p\gamma})^{-1}, \quad (3)$$

where $\theta_{p\gamma}$ is the incidence angle between the proton and the photon in the lab frame. This condition is independent of whether the proton is free or bound in a nucleus; in either case, photomeson production occurs in nearly the same way. In the rest frame of the nucleus, the photons have an energy of about 300 MeV. This energy is much larger than the binding energy per nucleon, so nuclear binding has little effect on the conversion of protons.

Young neutron stars ($\text{tage} < 10^5$ yr) typically have temperatures of $T_\infty \approx 0.1$ keV ($= 1.2 \times 10^6$ K). Typical photon energies near the surface are $\epsilon_\gamma \approx 2.8kT_\infty(1 + z_g) \sim 0.4$ keV, where $z_g \approx 0.4$ is the gravitational redshift. The proton threshold energy for the delta resonance is then $\epsilon_{p,\text{th}} \approx T^{-1}_{0.1\text{keV}} f_g$ PeV, where $T_{0.1\text{keV}} \equiv (kT_\infty/0.1 \text{ keV})$. As we show below, the conversion, if it happens, must occur near the stellar surface. Hence, protons scatter with photons in a lab frame scattering angle of $\theta_{p\gamma} \approx 90^\circ$, giving $f_g \approx 1$. (We neglect the effects of gravitational light bending.) In comparing the threshold energy $\epsilon_{p,\text{th}}$ to the radiation loss limit $\epsilon_{\text{max}}$, it appears that radiation losses will not preclude protons from reaching the $\Delta$ resonance, even for heavy nuclei.

Is the accelerating potential strong enough to bring protons to the $\Delta$ resonance? The maximum energy per proton is $\epsilon_{p,\text{th}}/A$. Since the protons are scattering with radiation that is being radiated isotropically from the star (we ignore the possibility of temperature variations across the surface), $\theta_{p\gamma} \leq 90^\circ$, and so $f_g > 1$. For the $\Delta$ resonance to be reached, we require that

$$B_{12}p_{\text{min}}^{-2}T_{0.1\text{keV}} \geq 3 \times 10^{-4}. \quad (4)$$

This condition, provided that $\mu \Omega < 0$, represents the most optimistic condition for neutrino production since we have assumed that the full potential $\Delta \Phi$ is available for accelerating ions. Eq. (4) is satisfied in many young pulsars, though not all. Magnetars, which have typical fields of $10^{15}$ G, spin rates of $4 - 8$ s and $T_{0.1\text{keV}} \approx 4 - 6$, are borderline neutrino emitters according to eq. (4), as found by [3]. In these estimates, we have neglected the possible quenching of the accelerating field by pair cascades produced through inverse-Compton scattering of the protons with the radiation field; numerical simulations of this effect indicate that the quenching will be negligible, even for the high surface temperatures we are considering [10]. Failure to detect neutrinos from pulsars, however, could mean that the field is strongly quenched.

Conversion Probability. For a significant neutrino flux to exist, the conversion probability for $p\gamma \rightarrow \Delta^+$ must be sufficiently high. The value of $f_g$ averaged over the surface increases rapidly with distance from the star, hence, the conversion must occur near the stellar surface or the threshold becomes unattainable. We suppose that the $\Delta$ resonance is reached before an altitude at which photons with $f_g \leq 2$, become unavailable. The photons with the lowest values of $f_g$ originate from the stellar limb. To crudely estimate $f_g$, we consider $\theta_{p\gamma}$ to be determined by the angle between the center of the star and the stellar horizon as “seen” by a proton at $r > R$, measured from the stellar center. With this definition, $f_g = 2$ corresponds to $r = 1.2R$. Some models of charge acceleration in pulsar magnetospheres find that significantly charge-starved regions can exist just above the stellar surface ($\sim 10^4$ cm), so that the charges receive most of their acceleration there [2, 3, 4], well below the altitude at which $f_g$ begins to exceed 2.

The mean free path for conversion at radius $r$ is $\lambda(r) = (n_\gamma \sigma_{p\gamma})^{-1}$, where $n_\gamma$ is the number density of the radiation field at radius $r$ and $\sigma_{p\gamma} \approx 5 \times 10^{-28}$ cm$^2$ is the cross section for $\Delta^+$ production. Assuming isotropic radiation from the stellar surface, the photon density there is $n_\gamma(R) = (a/2.8k)[(1 + z_g)T_\infty]^{-3} \approx 9 \times 10^{19} T_{0.1\text{keV}}^{-3}$ cm$^{-3}$, where $a$ is the radiation density constant, and $n_\gamma(R) = n_\gamma(R)/R^2$. The mean free path at the stellar surface is $\lambda(R) \approx 2 \times 10^{-3} T_{0.1\text{keV}}^{-3}$ cm. The probability $P$ that a proton has not been converted changes with $r$ as $dP/P = -dr/\lambda(r)$. By the time a proton starting at the surface has reached radius $r$, the probability of conversion is $P_{\text{conv}}(r) = 1 - P(r)$. Requiring conversion in the range $R \leq r \leq 1.2R$ gives $P_{\text{conv}} \approx 0.027 T_{0.1\text{keV}}^{-3}$. For the surface temperatures we are interested in ($T_{0.1\text{keV}} \approx 1$), the radiation field is quite optically thin to the conversion process. Hence we can expect the conversion of only one proton per nucleus, if there is a conversion at all. Because the energy imparted to the $\Delta^+$ is much larger than the binding energy per nucleon, the $\Delta^+$ will be ejected from the nucleus. The pulsar emission mechanism will be essentially unaffected, since so few nuclei are affected. The probability of photodisintegration is negligible.

The Neutrino Energy. The average fraction of energy transferred from the proton to the pion is $\sim 0.2$, or $200 T_{0.1\text{keV}}^{-1}$ TeV, corresponding to a Lorentz factor...
The Neutrino Flux. The accelerated protons are far more energetic than the radiation field with which they are interacting. Any pions produced through the $\Delta$ resonance, and hence, any muon neutrinos, will be far more energetic than the radiation field with which they are interacting. The resulting neutrino energy is then

$$\epsilon_{\nu_\mu} \simeq 50 T_{0.1 \text{keV}}^{-1} \text{TeV}. \quad (5)$$

Large-area neutrino detectors use the Earth as a medium for conversion of a muon neutrino to a muon, which then produces Cerenkov light in the detector. The conversion probability in the Earth is $P_{\nu_\mu \to \mu} \simeq 1.3 \times 10^{-6} (\epsilon_{\nu_\mu}/1 \text{ TeV})$ where $\epsilon_{\nu_\mu}$ is the energy of the incident neutrino. Combining eqs. $\text{[4]}$ and $\text{[6]}$ gives a muon event rate of

$$\frac{dN}{dAdt} = \phi_\nu P_{\nu_\mu \to \mu}$$

$$\simeq 10^5 Z^{-1} f_\phi f_d B_{12} p_{\text{ms}}^{-1} T_{0.1 \text{keV}}^2 \mu \text{km}^{-2} \text{ yr}^{-1}. \quad (7)$$

As an example, if $T_{0.1 \text{keV}} = 1$, $f_\phi = 0.1$, $f_d = 0.1$, $p_{\text{ms}} = 10$, $d_{\text{kpc}} = 3$, $Z = 2$, the muon flux would be $\sim 6 \text{ km}^{-2} \text{ yr}^{-1}$ at a neutrino energy of $\simeq 50 \text{ TeV}$. The rate given by eq. $\text{[4]}$ is model independent and quite general, provided that young neutron stars succeed in accelerating positive ions to the $\Delta$ resonance.

Detectability. For a neutron star to be a detectable neutrino pulsar, it must satisfy eq. $\text{[4]}$, and be sufficiently close as to give a strong flux. For a neutron star to be a detectable neutrino pulsar, it must satisfy $B_{12} p_{\text{ms}}^{-2} T_{0.1 \text{keV}} > 3 \times 10^{-4}$ (eq. $\text{[4]}$), and be sufficiently close as to give a strong flux. Potentially interesting sources and upper limits for their muon event rates are given in Table 1. We have optimistically included SN1987a in the Table, in case this supernova remnant contains a neutron star. We have estimated the background above 50 TeV due to atmospheric cosmic ray events using the flux given by $\text{[12]}$; for detectors such as AMANDA-II and ANTARES, with angular resolutions of $\sim 1^\circ$, the atmospheric background above 50 TeV contributed over several years will be so low that the detection of a single muon would represent a statistically significant neutrino detection.

Discussion. Results of 607 d of data from AMANDA-II are now available $\text{[13, 14]}$. Cass A and the Crab pulsar were not detected as neutrino sources. Cass A has not been observed as a pulsar, and so would not be expected to be a source in this model. The Crab pulsar would be a strong source, but only if $\nu \cdot \Omega < 0$. If the Crab is a neutrino pulsar, and the temperature is close to the observational upper limit, lack of detection by AMANDA-II requires $f_d < 0.01$ ($Z = 2$), which seems improbably low in the face of current models of charge depleted gaps. It seems likely that the Crab is simply not a neutrino pulsar, perhaps because $\nu \cdot \Omega > 0$. (The threshold condition eq. $\text{[4]}$ would be easily met even for much lower temperatures than the upper limit given in Table 1).

Should AMANDA-II have seen neutrinos from other

| Source | $d_{\text{kpc}}$ | age | $p_{\text{ms}}$ | $B_{12} T_{0.1 \text{keV}}$ | $f_\phi$ | $dN/dAdt$ |
|--------|-----------------|-----|---------------|-----------------|--------|----------|
| Crab   | 2               | $10^3$ | 33 | 3.8 $\leq 1.7$ | 13 | 0.14 | 1200 |
| Vela   | 0.29            | $10^{4.2}$ | 89 | 3.4 | 0.6 | 14 | 0.05 | 800 |
| J0205+64 | 3.2           | $10^{2.9}$ | 65 | 3.8 $\leq 0.9$ | 15 | 0.04 | 20 |
| B1509-58 | 4.4           | $10^{3.2}$ | 151 | 15 | 1? | 16 | 0.26 | 130 |
| B1706-44 | 1.8           | $10^{4.3}$ | 102 | 3.1 | 1? | 16 | 0.13 | 120 |
| B1823-13 | 4.1           | $10^{4.3}$ | 101 | 2.8 | 1? | 16 | 0.34 | 60 |
| Cass A | 3.5 $\text{[16]}$ | 300 | 10? | 1? | 4 $\text{[16]}$ | 1? | 1300 |
| SN 1987a | 50        | 17 | 1? | 4? | 1? | 1? | 1300 |
neutrino pulsars? There are now 64 known pulsars that are within 10 kpc of Earth and younger than $10^5$ yr [17], detected mostly by the Parkes Radiopulsar Survey. Any of these is a potential neutrino pulsar. Because the Parkes telescopes are located in the southern hemisphere, only 13 of the 64 radio pulsars are in the northern sky, the part visible to AMANDA-II. To make an estimate of the probability of detection of a random neutrino pulsar by AMANDA-II, suppose that AMANDA-II were located at the North Pole, observing southern-sky sources. We can then use a sample of the 51 pulsars from the southern sky to assemble a probability distribution for the rates. We took $T_{0,1keV} = 1$, $f_d = 0.5$ and $Z = 2$ in all cases, $f_b$ in the cases that it has been measured, and $f_b = 0.1$ in all other cases. Using these uncertain, but very conservative numbers, we find only ~1 pulsar that satisfies eq. 4 and $\mu \cdot \Omega < 0$, so it is not surprising that AMANDA-II has not yet seen a neutrino pulsar. Given the small number of pulsars known in the northern sky, our model cannot be statistically constrained by AMANDA-II. AMANDA-II’s successor, IceCube, with ten times the effective area, might reveal neutrino pulsars. Moreover, in the southern sky there are a number of promising candidates that might be detected by ANTARES (expected to go into operation during 2005), but that are inaccessible to AMANDA-II; these include Vela, B1509-58, B1706-44, B1823-13 and possibly SN 1987a. There are other candidates in the southern sky, none with measured temperatures, but assuming $T_{0,1keV} \geq 1$, there are nine known pulsars that satisfy eq. 4, are within a distance of 5 kpc and are younger than $10^5$ yr and therefore likely to have $T_{0,1keV} \sim 1$. These give typical muon event rates of $\sim f_d Z^{-1}(20 - 130) \text{ km}^2 \text{ yr}^{-1}$; three of these candidates are listed in Table 1.

The most promising candidate source in the southern sky is the Vela pulsar, which if detected by ANTARES, would give an event rate of $80 Z^{-1} f_d \text{ yr}^{-1}$. For $Z = 2$, the source would be detectable over a year of observing time even if the acceleration region is charge depleted to $\sim 3\%$ of the Goldreich-Julian density. For modest depletion ($f_d \sim 1/2$), Vela could be detected in under three weeks. If we are unfortunate, and Vela has $\mu \cdot \Omega > 0$, it will not be a neutrino pulsar, and we must look for weaker sources. For the other candidates to be detectable by ANTARES, B1508-58 and B1706-44 might be detected in about four months for $f_d \simeq 1/2$ and $Z = 2$. After the first year of data from ANTARES, statistical constraints will be possible even if there are no detections, since the the properties of pulsars in the southern sky are well understood. No detections would mean that photomeson production is negligible or nonexistent, providing an interesting constraint on the energetics of the magnetosphere. A detection would allow a determination of $Z^{-1} f_d$, and hence, the charge density in the acceleration region. We stress that the rates appearing in Table 1 are upper limits; they could be significantly reduced by the factor $Z^{-1} f_d$.

We conclude by pointing out that neutrino pulsars could be among the strongest sources of high-energy muon neutrinos in the sky, and therefore, might be the first sources to be detected. (See [20, 21] for a review of other models). We will present the energy spectrum of neutrino pulsars in a forthcoming publication.

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