Production of high-energy $\mu$ neutrinos from young neutron stars

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Young, rapidly rotating neutron stars could accelerate protons to energies of $\sim 1$ PeV close to the stellar surface, which scatter with x-rays from the stellar surface through the $\Delta$ resonance and produce pions. The pions subsequently decay to produce muon neutrinos. We find that the energy spectrum of muon neutrinos consists of a sharp rise at $\sim 50$ TeV, corresponding to the onset of the resonance, above which the flux drops as $\epsilon^{-2}$ up to an upper-energy cut-off that is determined by either kinematics or by the maximum energy to which protons are accelerated. We predict event rates as high as $10^{-5}$ to $10^{-3}$ km$^{-2}$ yr$^{-1}$ from relatively young, close neutron stars. Such fluxes would be detectable by IceCube.

1. Introduction

A new window in high-energy astronomy is opening as existing neutrino detectors are improved and new ones are developed. Since neutrinos produced in astrophysical systems are unimpeded by interstellar matter on their way to Earth, detections will provide a new way to study the highest energy phenomena in the Universe. Astrophysical neutrinos are expected to arise in many environments in which neutrinos are produced by the decay of pions created through hadronic interactions ($pp$) or photomeson production ($p\gamma$). Neutrinos may be produced by cosmic accelerators, like those in supernova remnants, active galactic nuclei, micro-quasars and gamma-ray bursts. To detect these neutrinos, several projects are underway to develop large-scale neutrino detectors under water or ice. AMANDA-II, in the South Pole, and Baikal are the two neutrino telescopes currently running, whereas ANTARES and NESTOR are under construction in the Mediterranean Sea. Those telescopes belong to a first generation with instrumented volume smaller than 0.02 km$^3$. The IceCube detector, with a volume of about 1 km$^3$, is under construction on the same site of AMANDA. The NEMO project is in its starting phase, and will be a cubic kilometer size detector located at Capo Passero, Southern Italy.

As neutrino astronomy comes of age, it is important to get some idea of what the sources might look like to aid in their detection. Recently, we proposed that young ($t_{\text{age}} \lesssim 10^5$ yr) and rapidly-rotating neutron stars could be intense neutrino sources. Here we summarize this work.

2. The Model

Neutron stars have enormous magnetic fields ($> 10^{12}$ G, typically) and high rotation rates (tens of Hertz), causing them to act as very powerful unipolar generators. Charges stripped off the highly-conductive surface are accelerated somewhere above the stellar surface. As the charges are accelerated along magnetic field lines, they emit curvature radiation, which scatters with the magnetic field and produces an $e^+e^-$ cascade. The cascade produces a radio beam along the magnetic field lines that open to infinity. If the beam angle and direction to Earth are favorable, the star can be detected as a radio pulsar, with one radio pulse per rotation period (in some cases, two pulses, when emission from both magnetic poles is seen).
If the stellar magnetic moment has a component anti-parallel to the spin axis (half of neutron stars), ions will be accelerated off the surface (see Fig.1). If energies of \( \sim 1 \) PeV per proton are attained, pions will be produced through photomeson production as the protons scatter with surface x-rays, producing a beam of \( \mu \)-neutrinos with energies above \( \sim 50 \) TeV. Detection of such neutrinos would be a fascinating discovery in its own right, and would provide an invaluable probe of the physical conditions that prevail in the magnetosphere of a neutron star.

For photomeson production to occur, ions must be accelerated to very high energies close to the stellar surface. How large might the accelerating potential be? Goldreich and Julian developed the first model of a quasi-static magnetosphere \([14]\). By assuming a dipolar configuration with magnetic axis parallel to the rotation axis, they showed that the potential drop across the field lines of a pulsar with angular velocity \( \Omega = 2\pi/p \) (where \( p \) is the period) from the magnetic pole to the last field line that opens to infinity is of magnitude

\[
\Delta \Phi = \frac{\Omega^2 BR^3}{2e^2} \simeq 7 \times 10^{18} B_{12} R_6^3 p_{ms}^{-2} \text{ Volts.} \quad (1)
\]

Here \( B = 10^{12} B_{12} G \) is the strength of the dipole component of the field at the magnetic poles, \( R = 10^6 R_6 \) cm is the stellar radius and \( p_{ms} \) is the spin period in milliseconds. In equilibrium (not realized in a pulsar), a co-rotating magnetosphere would exist in the regions above the star in which magnetic field lines closed; the charge density would be \( \rho_q \simeq eZn_0 \simeq B/pc \) (cgs units), where \( n_0 \) is the equilibrium number density of ions that would short out the component of the electric field along the magnetic field. Deviation from corotation will lead to charge-depleted gaps somewhere above the stellar surface, through which charges will be accelerated to relativistic energies \([15,16]\). Suppose that charge depletion occurs near the stellar surface, with a characteristic density \( f_d n_0 \), where \( f_d < 1 \) is an unknown depletion factor. If the neutron star is young, its surface will emit 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 \( \Delta^+ \) quickly decays to a \( \pi^+ \), and muon neutrinos are produced through the following channel:

\[
p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+ \rightarrow n\nu_\mu\mu^+ \rightarrow n\nu_\mu e^+ \nu_e \bar{\nu}_\mu. \quad (2)
\]

The proton energy threshold \( \epsilon_p \) for \( \Delta^+ \) production is given by

\[
\epsilon_p \geq 0.3 \text{ GeV}^2 f_g, \quad f_g \equiv (1 - \cos \theta)^{-1}, \quad (3)
\]

where \( \epsilon_\gamma \) is the photon energy and \( \theta \) is the incidence angle between the proton and the photon in the lab frame. Young neutron stars typically have temperatures of \( T_\infty \simeq 0.1 \) keV, and proton energies \( \epsilon_p \geq 2.8kT_\infty (1 + z_0) \sim 0.4 \) keV, where \( z_0 \simeq 0.4 \) is the gravitational red-shift and \( T_\infty \) is the surface temperature measured at infinity. The proton threshold energy for the \( \Delta \) resonance is then \( \epsilon_{p,th} \simeq T_0^{-1} (1 + z_0) f_g \) PeV, where \( T_0 = 1 \) keV \( \equiv (kT_\infty/0.1 \text{ keV}) \). Therefore, if the potential along field lines is only \( \sim 1\% \) of the full potential \( \Delta \Phi \) across field lines in the equilibrium magnetosphere, protons can reach the \( \Delta \) resonance.

Before continuing, we mention that our assumption that PeV protons can be produced in the stellar magnetosphere is a strong one; it is generally thought that pair production near the stellar surface will quench the field and limit the potential drop along the field to \( \sim 1 \) TeV \([17,18]\). These calculations are subject to numerous uncertainties, and apply only in equilibrium, not the case in a neutron star magnetosphere. Though potential drops as high as \( \sim 1 \) PeV might not be attainable, we consider the possibility sufficiently interesting to explore further and to possibly confirm or refute with future neutrino observations. Even null results would provide a valuable probe of the poorly-understood neutron star magnetosphere, confirming a limit that so far has only a theoretical basis.

Assuming that a potential of order \( \Delta \Phi \) is available for acceleration along field lines, a necessary condition for the \( \Delta \) resonance to be reached is

\[
B_{12} p_{ms}^2 T_0 \geq 3 \times 10^{-4}. \quad (4)
\]

Taking \( T_0 = 1 \) keV, typical of pulsars younger than \( \sim 10^5 \) yr, there are 10 known pulsars within
distance of 8 kpc that satisfy this condition \[19\], about half of which should have positively-charged magnetic poles; these are potentially detectable sources of $\mu$ neutrinos. The best candidates are young neutron stars, which are usually rapidly spinning and hot. In the photomeson production process of eq.(2), the muon neutrinos receive 5% of the energy of the proton. Typical proton energies required to reach resonance are $\sim 1$ PeV, so the expected $\mu$ neutrino energies will be $\sim 50$ TeV. The conversion probability for a proton is small ($\lesssim 1\%$); only a small number of protons are excited to the $\Delta$ resonance and the pulsar beam is essentially unaffected. Moreover, since the accelerated protons are far more energetic than the radiation field with which they interact, any pions produced through the $\Delta$ resonance, and hence, any muon neutrinos, will be moving in nearly the same direction as the proton was when it was converted. The radio and neutrino beams will be approximately coincident, so that some radio pulsars might also be detected as neutrino sources. We see the radio beam for only a fraction $f_b$ of the pulse period, the duty cycle. Typically, $f_b \simeq 0.1 - 0.3$ for younger pulsars. We take the duty cycle of the neutrino beam to be $f_b$ (but see below). In Ref. [13], we estimated the phase-averaged neutrino flux at Earth resulting from the acceleration of positive ions, at a distance $d$ from the source, to be

$$\phi_{\nu} \simeq 2c f_b f_d (1 - f_d) n_0 \left( \frac{R}{d} \right)^2 P_c,$$

(5)

where $f_d n_0$ is the space charge density in the depleted region, where proton acceleration is taking place, and $P_c$ is the conversion probability. For the purposes of calculating the spectrum, we use the following differential neutrino flux:

$$\frac{d\phi_{\nu}}{d\epsilon_{\nu}} = 2c f_b f_d (1 - f_d) n_0 \left( \frac{R}{d} \right)^2 \frac{dP_c}{d\epsilon_{\nu}}.$$

(6)

We are interested in obtaining upper limits on the flux and so take $f_d = 1/2$ and $Z = 1$. The detailed calculation of the spectrum $dP_c/d\epsilon_{\nu}$ has been reported in [13], and we summarize these results next.

3. Neutrino Spectrum

In calculating the neutrino spectrum, we have accounted for the fact that the proton acceleration takes place over a finite distance above the
Table 1
Estimated upper limits on the $\mu$ fluxes at Earth. Numbers followed by question marks indicate guesses. Radio pulsar spin parameters were taken from the catalogue of the Parkes Radiopulsar Survey (www.atnf.csiro.au/research/pulsar/psrcat/). Temperatures and limits on temperatures were taken from the references indicated. The temperature upper limits on the Crab and J0205+64 were used. The integrated conversion probability $P_c$ is reported for the case of linear acceleration, and assuming $L = 0$.

| Source     | $d_{\text{kpc}}$ | age yr | $p_{\text{ms}}$ | $B_{12}$ | $T_{0.1\text{keV}}$ | $f_b$ | $P_c$ | $dN/dAdt$ km$^{-2}$ yr$^{-1}$ |
|------------|-----------------|--------|-----------------|---------|-------------------|------|-------|-------------------------------|
| Crab       | 2               | $10^3$ | 33              | 3.8     | $\leq 1.7$        | 0.14 | 1.6 x $10^{-3}$ 45            |
| Vela       | 0.29            | $10^4.2$ | 89              | 3.4     | 0.6 $\text{[21]}$ | 0.04 | 7.2 x $10^{-5}$ 25            |
| J0205+64   | 3.2             | $10^2.9$ | 65              | 3.8     | $\leq 0.9$        | 0.05 | 2.4 x $10^{-4}$ 1             |
| B1509-58   | 4.4             | $10^3.2$ | 151             | 15      | 1? $\text{[22]}$  | 0.26 | 3.4 x $10^{-4}$ 5             |
| B1706-44   | 1.8             | $10^4.3$ | 102             | 3.1     | 1? $\text{[22]}$  | 0.13 | 3.4 x $10^{-4}$ 5             |
| B1823-13   | 4.1             | $10^4.3$ | 101             | 2.8     | 1? $\text{[22]}$  | 0.34 | 3.4 x $10^{-4}$ 2             |
| Cass A     | 3.5             | 300    | 10?             | 17      | 4 $\text{[23]}$  | 0.17 | 2.1 x $10^{-2}$ 50            |
| SN 1987a   | 50              | 17     | 1?              | 1?      | 4? $\text{[23]}$ | 0.17 | 2.1 x $10^{-2}$ 3             |

Surface. We have considered an acceleration law of the form

$$\epsilon_p = \frac{\epsilon_0^2}{\epsilon_\gamma} \left(\frac{z}{L}\right)^\gamma$$  \hspace{1cm} (7)

where $\epsilon_0^2 \equiv 0.3 \text{ GeV}^2$, $z$ is the height above the stellar surface and $L$ is the length scale over which the proton is accelerated before reaching sufficient energy to undergo the $\Delta$ resonance. We consider linear acceleration ($\gamma = 1$), corresponding to a constant electric field in the charge-depleted zone, and quadratic acceleration ($\gamma = 2$), corresponding to an accelerating field that grows linearly with height. We have also accounted for the finite width of the $\Delta$ resonance in the cross section.

The spin parameters of 8 potential neutrino sources are given in Table 1. In Fig. 2 we show the neutrino energy flux for the Crab pulsar, assuming its surface temperature is equal to the observational upper limit. The Crab pulsar is located in the northern hemisphere and so is monitored by AMANDA-II. The spectrum calculated in our model is represented by the solid line, and it has been calculated by assuming linear acceleration. For comparison, we also show two independent calculations obtained by Bednarek and Protheroe \textit{[21]} (dotted line), and Guetta and Amato \textit{[25]} (dashed line) in the case that neutrinos are emitted from the nebula. Those models predict a low muon event rate in comparison to our model, as shown in Ref. \textit{[26]}. In our model, the spectrum begins sharply at

$$\epsilon_\nu \approx 70 T_{\text{keV}}^{-1} \text{ GeV},$$  \hspace{1cm} (8)

corresponding to the onset of the resonance. At higher energies, the spectrum drops approximately as $\epsilon_\nu^{-2}$, as the phase space for conversion becomes restricted; higher energy neutrinos are produced by protons that have been accelerated to greater heights, where the photon density is lower and solid angle subtended by the star (as seen by the proton) is smaller. At some maximum energy, the spectrum is suddenly truncated by either kinematics (solid curve) or the termination of the proton acceleration as limited by the magnitude of the acceleration gap (not shown, since this cut-off cannot be predicted).
4. Estimated Count Rates and Discussion

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 $P_{\nu\mu\rightarrow\mu}\simeq1.3\times10^{-9}(\epsilon_{\nu}/1\text{ TeV})$, where $\epsilon_{\nu}$ is the energy of the incident muon neutrino [27]. The muon event rate is

$$\frac{dN}{dAdt} = \int d\epsilon_{\nu} \frac{d\phi_{\nu}}{d\epsilon_{\nu}} P_{\nu\mu\rightarrow\mu}. \tag{9}$$

Estimated conversion probabilities for the Crab, Vela and 6 other pulsars are given in Table 1 (column 8) for a characteristic acceleration length $L = 0.1$. The final column gives the estimated event rates. Complete consideration of the kinematics gives event rates a factor of $\sim 10 - 30$ lower than estimated in our previous paper [12].

Neutrinos are produced at relatively high rates only if the protons are accelerated through the resonance close to the star. In this case, we obtain integrated count rates of several to $\sim 50 \text{ km}^{-2} \text{ yr}^{-1}$. Such count rates should be easily detected by IceCube, and possibly by AMANDA-II or ANTARES with integration times of about a decade (IceCube is planned to have replaced AMANDA-II by then) for depletion factors of $f_d \simeq 1/2$. While the characteristics of the spectrum presented here are robust, we caution that the event rates we obtain are very rough upper limits, subject to many uncertainties. For example, we have assumed that the neutrinos are beamed into the same solid angle as the radio beam, which might not be a correct assumption. The radio beam is thought to be produced at about $10R$ [28]. In our model, the pions are produced much closer to the star. They then propagate to $\sim 1000R$ before decaying to neutrinos. At this distance from the star, the field is unlikely to be dipolar, and it is difficult to say anything definite about the distribution of pion velocities in this region. If the neutrinos form a beam, the beam may be more or less collimated than the radio beam. If it is more collimated, the neutrino event rates could be higher than estimated here.
Results of 807 d of data from AMANDA-II are now available [29]. AMANDA-II has detected 10 events (over a background of 5.4) from the direction of the Crab pulsar, with energies higher than 10 GeV. This result, though intriguing, is not statistically significant; IceCube will be able to confirm or refute this result. While it would be more exciting to see neutrinos from pulsars, the accumulation of null results over the next decade would be interesting as well; it would probably mean that photomeson production is ineffective or non-existent in the neutron star magnetosphere, thus providing a bound on the accelerating potential that exists near the neutron star surface.

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