Neutrino Pulsars

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**Bottom line:**
Young neutron stars could be the brightest sources of high-energy neutrinos (~50 TeV).

In collaboration with F. Burgio (University of Catania, Italy)
Overview

- Neutrino astronomy
- A physical mechanism for high-energy neutrino production from pulsars
- Estimates of neutrino flux rates at Earth
- Prospects for detection
Some models of neutrino production

- **pp interactions in AGN** (Nellen et al. 93)
- **pγ in AGN** (Stecker & Salamon 96)
- **pγ in extragalactic photoproduction sources** (Mannheim et al. 00)
- **pγ and pp in blazar jets** (Mannheim 95)
- **pγ due to UHE CR from radio galaxies interacting with the CMBR** (Rachen & Biermann 93; Protheroe & Johnson 96)
- **Gamma-ray bursts** (Waxman & Bahcall 97)
- **pγ and pp interactions in plerions** (Bednarek & Protheroe 97; Bednarek 03; Guetta & Amato 03)
Neutrino observatories

AMANDA-II, ANTARES, IceCube, NEMO, NESTOR

Detection principle

Angular resolution of $\sim 1^\circ$!!
Complete list of extraterrestrial sources of high-energy neutrinos by AMANDA-II

Muons from cosmic rays hitting the atmosphere have been seen.
Neutron stars might be sources too.
Photomeson production
(the “Δ resonance”)

\[ p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+ \rightarrow n\nu_\mu\mu^+ \rightarrow ne^+\nu_e\nu_\mu\bar{\nu}_\mu \]

The threshold for this reaction is:

\[ \epsilon_p \geq \left( \frac{T_\infty}{0.1 \text{ keV}} \right)^{-1} \text{ PeV} \]

Protons accelerated off the surface of a young neutron star could undergo photomeson conversion with the soft x-rays from the surface. (c.f. Zhang, Dai, Mészáros, Waxman & Harding 03).
Is it possible to get protons to ~1 PeV?
The equilibrium magnetosphere
(Goldreich & Julian 1969)

From Ruderman & Sutherland (76)

Potential drop across B of:

\[ \varepsilon_\perp \sim 100 Z B_{12} \left( \frac{p}{10 \text{ ms}} \right)^{-2} \text{ PeV} \]

Corotating charge of density:

\[ n_{GJ} \sim 10^{13} Z B_{12} \left( \frac{p}{10 \text{ ms}} \right)^{-1} \text{ cm}^{-3} \]

“Light cylinder”

Sign of charges in open-field region is determined by sign of \( \mu \Omega \).
The question of magnetospheric physics

- In the equilibrium magnetosphere, there is no charge acceleration ($E \cdot B \neq 0$).
- For acceleration, need $E \cdot B \neq 0$, which requires $n < n_{GJ}$, somewhere.
- How and where does this gap develop?

1. Is it an inner gap, close to the star? (see, e.g., Ruderman & Sutherland 75; Arons & Scharlemann 79; Harding & Muslimov 98).
2. Or is it an outer gap, far from the star? (Cheng, Ho & Ruderman 86).

Talks later today by Tomokhin and Spitkovsky
Suppose charge depletion occurs near the surface
(Ruderman & Sutherland 75; Arons & Scharlemann 70; Harding & Muslimov 98)

Charge-depleted region

\[ n << n_{GJ} \]

\[ \mathbf{E} \cdot \mathbf{B} \neq 0 \implies \text{charge acceleration} \]

A significant fraction of

\[ \varepsilon_\Phi \sim 100ZB_{12} \left( \frac{p}{10 \text{ ms}} \right)^{-2} \text{ PeV} \]

can be attained.
Conjecture to be tested by neutrino observations

A strong accelerating field exists near the stellar surface that is sufficient to bring protons to the $\Delta$ resonance:

$$p\gamma \longrightarrow \Delta^+ \longrightarrow n\pi^+ \longrightarrow n\nu_\mu\mu^+ \longrightarrow ne^+\nu_e\nu_\mu\bar{\nu}_\mu$$
Requirements

- Field is properly oriented: $\mu \cdot \Omega < 0$ (to accelerate positive ions). Half of pulsars.
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- Field is properly oriented: $\mu \cdot \Omega < 0$ (to accelerate positive ions). Half of pulsars.
- Sufficiently strong accelerating field exists to bring protons to resonance.
How strong an accelerating field?

Energy threshold for the proton is

$$\varepsilon_p \geq \left( \frac{T_\infty}{0.1 \text{ keV}} \right)^{-1} \text{ PeV}$$

Compare to potential energy across the field:

$$\varepsilon_\perp \sim 100 Z B_{12} \left( \frac{p}{10 \text{ ms}} \right)^{-2} \text{ PeV}$$

Need an accelerating electric field of strength:

$$E_\parallel \sim 0.01 E_\perp$$
Can we get protons to \( \sim 1 \) PeV?

- Pair creation will quench the field at some point.
- There will be losses to curvature radiation.
Curvature radiation loss limit

\[ \epsilon_{\text{max}} \simeq 20 \left( \frac{A}{Z^2} \right)^{1/3} \text{ PeV per nucleon} \]

⇒ Not a limitation
Necessary condition on stellar parameters for resonance

\[ B_{12} \left( \frac{p}{10 \text{ ms}} \right)^{-2} \left( \frac{T_{\text{surf}}}{0.1 \text{ keV}} \right) > 0.03 \]

Satisfied by dozens of close pulsars...probably.
Neutron stars stay hot for a long time

Yakovlev & Pethick 04
Necessary condition on stellar parameters for resonance

\[ B_{12} \left( \frac{p}{10 \text{ ms}} \right)^{-2} \left( \frac{T_{surf}}{0.1 \text{ keV}} \right) > 0.03 \]

There are 64 known pulsars within 10 kpc younger than \(10^5\) yr.

There are 9 within 5 kpc, younger than \(10^5\) yr, and that satisfy this condition if \(T_{surf} = 0.1\) keV.
Requirements

- Field is properly oriented: $\mu \cdot \Omega < 0$ (to accelerate positive ions). Half of pulsars.
- Sufficiently strong accelerating fields exist to bring protons to resonance.
- The acceleration must occur *near the surface* (within $\sim 0.5R$).
Resonance can happen only near the surface.

Resonance occurs for:

$$\varepsilon_p = \left( \frac{T_\infty}{0.1 \text{ keV}} \right)^{-1} \frac{1}{1 - \cos \theta} \text{ PeV}$$
Also, the conversion probability is low

\[ P_{\text{conv}} \approx 0.02 T_{0.1\text{keV}}^3 \]

\[ \Rightarrow \text{few protons are affected.} \]
If protons are converted...

\[ p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+ \rightarrow n\nu_\mu\mu^+ \rightarrow ne^+\nu_e\nu_\mu\bar{\nu}_\mu \]

Pions move along the field lines before decaying...
⇒ a radio pulsar could be a “neutrino pulsar”.
Energies

\[ p\gamma \longrightarrow \Delta^+ \longrightarrow n\pi^+ \longrightarrow n\nu_{\mu}\mu^+ \longrightarrow ne^+\nu_e\nu_{\mu}\bar{\nu}_{\mu} \]

Protons

\[ \varepsilon_p \simeq T_{0.1keV}^{-1} \text{ PeV} \]

Pions

\[ \varepsilon_\pi \simeq 200 T_{0.1keV}^{-1} \text{ TeV} \]

\( \mu \) neutrinos

\[ \varepsilon_{\nu_{\mu}} \simeq 50 T_{0.1keV}^{-1} \text{ TeV} \]
Best candidate neutron stars are...

- Close
- Hot
- Rapidly spinning

And must have $\mu \cdot \Omega < 0$
A crude flux estimate
(Link & Burgio 2005, PRL, 94, 181101)

\[ \phi_v \approx c f_b f_d n_{GJ} \left( \frac{R}{d} \right)^2 P_{\text{conv}} \]

depletion factor (<1)

neutrino flux
beam duty cycle

Muon number flux in a large-area detector

\[ \frac{dN}{dA dt} = \phi_v P_{\nu \mu \rightarrow \mu} \sim 10^5 Z^{-1} f_d f_b B_{12} p_{ms}^{-1} d_{kpc}^{-2} T_{0.1 keV}^2 \text{ km}^{-2} \text{ yr}^{-1} \]

at an energy

\[ \varepsilon_{\nu \mu} \sim 50 T_{0.1 keV}^{-1} \text{ TeV} \]
Some promising candidates

Detector area = 0.1 km$^2$
Observing time = 1 year

<table>
<thead>
<tr>
<th>Source</th>
<th>Hemisphere</th>
<th>(muon counts)(\times f_d Z^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab</td>
<td>northern</td>
<td>120</td>
</tr>
<tr>
<td>J0205+64</td>
<td>northern</td>
<td>10?</td>
</tr>
<tr>
<td>Vela</td>
<td>southern</td>
<td>80</td>
</tr>
<tr>
<td>B1509-58</td>
<td>southern</td>
<td>10?</td>
</tr>
</tbody>
</table>

At muon energies $\geq 50$ TeV
Calculating the neutrino spectrum

Resonance occurs for:

$$\varepsilon_p = \left( \frac{T_\infty}{0.1 \text{ keV}} \right)^{-1} \frac{1}{1 - \cos \theta} \text{ PeV}$$

$$\varepsilon_p = \varepsilon_{p,0} \left( \frac{z}{L_{\text{acc}}} \right)^2$$
Predicted neutrino spectrum

(Crab Spectrum \( T_{0.1\text{keV}} = 1 \))
Other models

- pp interactions in AGN (Nellen et al. 93)
- $p\gamma$ in AGN (Stecker & Salamon 96)
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Predicted neutrino spectrum

Crab Spectrum ($T_{0.1\text{keV}}=1$)

- $L_{\text{acc}}=0.6 \text{ R}$
- $L_{\text{acc}}=0.2 \text{ R}$
- $L_{\text{acc}}=0.06 \text{ R}$
- $L_{\text{acc}}=0.02 \text{ R}$

$\frac{d\Phi_v}{d\epsilon_v}$ ($\text{GeV}^{-1} \text{m}^{-2} \text{s}^{-1}$)

$\epsilon_v$ (TeV)

Other models
Conclusions

- Neutrino pulsars, *if they exist*, could be the brightest sources in the sky above ~ 50 TeV. They might be the first sources detected.

- Detection would allow direct constraints on the physical conditions in the neutron star magnetosphere.

- Lack of detection would also allow constraints.