HIGH-ENERGY NEUTRINOS FROM GEMINGA

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ABSTRACT

AMANDA-II recently published a high-energy neutrino signal towards Geminga which has the highest statistical significance ($2.6\,\sigma$) over its 26 sample of point sources. While it cannot be considered as a discovery, it is nevertheless tantalizing that the statistically more relevant signal is found just towards the nearest pulsar. Moreover, this signal corresponds to about 1 neutrino-induced muon per km^2 per year with energy above 1 TeV in a detector like ICECUBE. We show that the same conclusion arises from an explicit emission model for Geminga, in which high-energy muon neutrinos are produced in pion photo-production processes involving the observed gamma-ray emission.

1. Introduction

Nowadays, high-energy neutrino astronomy may well be on the verge to become a reality thanks to currently operating or planning large-area neutrino telescopes like ICECUBE, ANTARES, NESTRO and NEMO [1)].

Among all possible astronomical source candidates, Galactic objects may be the first detected because their comparatively smaller distances can make them detectable, in spite of the fact that their neutrino luminosity is expected to be considerably lower than for other extragalactic sources. As far as pulsars are concerned, this is especially true for Geminga [2)], which is the nearest pulsar to the Earth at distance $D \simeq 160\,\mathrm{pc}$. So, the question naturally arises as to whether Geminga is a sufficiently bright source of high-energy neutrinos.

Surprisingly, this issue is still unsettled, and our goal is to show that theoretical arguments strongly support the expectation that the high-energy neutrino flux from Geminga may be large enough so as to be potentially observable with ICECUBE [3)], ANTARES [4)], NESTRO [5)] and NEMO [6)].

Available observational results also make the case of Geminga particularly intriguing. For, AMANDA-II recently published its final results for 26 point sources [7], and while no real discovery of high-energy neutrinos is reported it is nevertheless tantalizing that the signal detected with highest statistical significance ($2.6\,\sigma$) corresponds indeed to Geminga. While chance can of course not be excluded, yet it looks striking that the most relevant signal happens to be just towards the nearest source. Moreover, it has been argued that this result would correspond to about 1 neutrino-induced muon per km^2 per year with energy above $1\,\mathrm{TeV}$ [8], which should be detectable with the neutrino telescopes available in the near future.

Remarkably enough, we will show that the same conclusion arises from an explicit emission model for Geminga, in which high-energy muon neutrinos are produced in pion photo-production processes involving the observed gamma-ray emission (due to curvature radiation from relativistic electrons).

2. Production mechanism

Cosmic neutrinos are the decay products of pions produced by proton-proton scattering and pion photo-production in non-thermal sources. The main assumption is that in all candidate sources a strong electromagnetic field is present that accelerates protons away from the source core. Furthermore, the presence of a dense target is a necessary ingredient in order to achieve a sufficiently high flux. For this reason, pulsar wind nebulae and pulsars in binary systems have attracted particular attention [9] and the dominant production mechanism is believed to be proton-proton scattering.

As far as isolated pulsars in a low-density environment are concerned, substantial neutrino production can only take place via pion photo-production. We recall that this process proceeds through the exchange of the Δ resonance as

$$p + \gamma \to \Delta \to n + \pi^+ \ , \tag{1}$$

which in turn produces muon neutrinos via the decay $\pi^+ \to \mu^+ + \nu_\mu$. Of course, also the process

$$p + \gamma \to \Delta \to p + \pi^0 \tag{2}$$

occurs with a comparable rate and gives rise to high-energy photons through the decay $\pi^0 \to \gamma + \gamma$. In order for pion photo-production to be kinematically allowed, the proton E_p and photon E_γ energies have to satisfy the condition

$$E_p\,E_\gamma > 0.3\,f_g\,\mathrm{GeV}^2 \ , \tag{3}$$

where $f_g \equiv (1-\cos\theta)^{-1}$ is a geometric factor depending on the photon-proton scattering angle θ in the laboratory frame. Needless to say, a dense enough target is still crucial and for this reasons one is led to regard as best candidates those particular pulsars which are embedded in a sufficiently strong radiation field. So far, two kinds of objects have been considered in this respect: magnetars [10] and young pulsars [11], which are both strong X-ray sources of thermal radiation.

Since Geminga is neither a magnetar nor a young pulsars, pion photo-production does not work as far as its X-ray thermal emission is concerned. Still, Geminga is an intense gamma-ray emitter via curvature radiation from relativistic electrons moving in the strong magnetic field. So, one wonders whether the gamma-ray photons themselves provide a sufficiently dense target for pion photo-production. As we will see, this turns out to be indeed the case.

For proton acceleration, we adopt the same mechanism envisaged in the case of magnetars [10] and young pulsars [11], which can be sketched as follows.

Consider a pulsar with radius R_*, rotation period P and angular velocity $\mathbf{\Omega}$ ($\Omega = 2\pi/P$). Within a corotating magnetosphere with dipolar magnetic field $\mathbf{B}$ and electric field $\mathbf{E}$, one has $\mathbf{E}\cdot\mathbf{B} = 0$ and the Goldreich-Julian maximal potential drop *across* the magnetic field lines is [12]

$$\Phi_\perp = \frac{2\pi^2 \, R_*^3 \, B_p}{c^2 \, P^2} \; , \tag{4}$$

where B_p denotes the value of the magnetic field at the pole. The Goldreich-Julian charge number density [12] reads

$$n_{gj} = \frac{B_p}{c \, e \, P} \; , \tag{5}$$

where c and e denote the velocity of light and the electric charge, respectively. Since in a corotating magnetosphere ions are forced to move along the magnetic field lines, they undergo no acceleration.

In fact, particle acceleration is believed to take place inside charge-depleted regions which depart from corotation – like *polar caps* [13] or *outer gaps* [14] – where the condition $\mathbf{E}\cdot\mathbf{B} \neq 0$ is met. Consequently, in these regions a potential drop *along* the magnetic field lines is present and can be conveniently represented as

$$\Phi_\parallel = \alpha \, \Phi_\perp = \frac{2\pi^2 \alpha \, R_*^3 \, B_p}{c^2 \, P^2} \; , \tag{6}$$

while the corresponding depleted charge number density can be written as

$$n_0 = f_d \, n_{gj} = \frac{f_d \, B_p}{c \, e \, P} \; , \tag{7}$$

with f_d parameterizing charge depletion. Assuming that $\mathbf{B}_p \cdot \mathbf{\Omega} < 0$, protons are accelerated away from the surface.

We proceed to inquire whether pion photo-production can occur in the case of Geminga, for which $R_* \simeq 10^6\,\mathrm{cm}$, $B_p \simeq 1.6 \cdot 10^{12}\,\mathrm{G}$ and $P \simeq 0.237\,\mathrm{s}$ [2]. In the first place, Eq. (6) entails that a proton acquires the energy

$$E_p \simeq 1.95 \cdot 10^2 \, \alpha \, \mathrm{TeV} \; . \tag{8}$$

Observations show that the gamma-ray luminosity of Geminga is $L_\gamma \simeq 10^{33}\,\mathrm{erg\,s^{-1}}$, with average photon energy $E_\gamma \simeq 0.2\,\mathrm{GeV}$ [15]. Therefore condition (3) becomes

$$\alpha > 7.7 \cdot 10^{-6}\, f_g \ , \tag{9}$$

which shows that pion photo-production actually occurs in Geminga even if the potential drop responsible for proton acceleration is a tiny fraction of the Goldreich-Julian maximal potential drop.

3. Expected neutrino flux

We start by computing the probability $P_\pi(r)$ that a single proton produces a pion via reaction (1) at a distance r from the pulsar centre in an environment with photon number density $n_\gamma(r)$. As is well known, the probability in question is given by

$$P_\pi(r) = 1 - \exp\left\{ - \int_{R_*}^{r} \frac{dr'}{\lambda(r')} \right\} \ , \tag{10}$$

where $\lambda(r) = (n_\gamma(r)\,\sigma_{\gamma,p})^{-1}$ is the proton mean free path and $\sigma_{\gamma,p} \simeq 5 \cdot 10^{-28}\,\mathrm{cm}^2$ is the cross section for pion photo-production. Hence, Eq. (10) becomes

$$P_\pi(r) = 1 - \exp\left\{ -\sigma_{\gamma,p} \int_{R_*}^{r} dr'\, n_\gamma(r') \right\} \ . \tag{11}$$

Actually, observations strongly suggest that the gamma-ray emission from Geminga originates from an outer spherical shell $\mathcal{S}$ with radius close to that of the light cylinder[16], which is presently $R_L \simeq 1.1 \cdot 10^9\,\mathrm{cm}$. The thickness of $\mathcal{S}$ can be supposed to be about $0.1\,R_L$. As a consequence, pion photo-production takes place only inside $\mathcal{S}$ and correspondingly Eq. (11) acquires the form

$$P_\pi(r) \simeq 1 - \exp\left\{ -\sigma_{\gamma,p} \int_{0.9\,R_L}^{R_L} dr\, n_\gamma(r) \right\} \ . \tag{12}$$

A rough estimate of $P_\pi(r)$ can be performed by assuming for simplicity that n_γ is constant inside $\mathcal{S}$. Moreover, since the gamma-ray emission is beamed, we suppose that only a fraction β of the outer surface of $\mathcal{S}$ emits photons. Consequently, we get

$$n_\gamma = \frac{L_\gamma}{4\pi\,\beta\, R_L^2\, E_\gamma\, c} \simeq 0.7 \cdot 10^7\, \beta^{-1}\,\mathrm{cm}^{-3} \ , \tag{13}$$

so that Eq. (12) yields

$$P_\pi(R_L) \simeq 3.9 \cdot 10^{-13}\, \beta^{-1} \ . \tag{14}$$

Next, we proceed to evaluate the number of muon neutrinos $dN^E_{\nu_\mu}/dt$ emitted by $\mathcal{S}$ per unit time. Clearly, the ν_μ number density at R_L is simply

$$n_{\nu_\mu} = n_0\, P_\pi(R_L) \simeq 1.53\, f_d\, \beta^{-1} \ , \tag{15}$$

where Eqs. (7) and (14) have been used. So, we get

$$\frac{dN^E_{\nu_\mu}}{dt} = 4\pi R_L^2\, \beta\, n_{\nu_\mu}\, c \simeq 2.2 \cdot 10^{37}\, f_d \ \mathrm{yr}^{-1} \ , \tag{16}$$

because neutrinos are produced only where photons are present, thereby implying that also the neutrino emission is beamed. Accordingly, the ν_μ number flux reaching the Earth from Geminga is

$$\frac{dN^\oplus_{\nu_\mu}}{dA\, dt} = \frac{1}{4\pi\, D^2} \frac{dN^E_{\nu_\mu}}{dt} \simeq 7.2 \cdot 10^4\, f_d \ \mathrm{Km}^{-2}\, \mathrm{yr}^{-1} \ . \tag{17}$$

Since the $\nu_\mu \to \mu$ conversion probability inside the Earth is [17)]

$$P(\nu_\mu \to \mu) \simeq 1.3 \cdot 10^{-6} \left(\frac{E_{\nu_\mu}}{\mathrm{TeV}} \right) \ , \tag{18}$$

the μ event rate in the detector reads

$$\frac{dN^\oplus_{\mu}}{dA\, dt} \simeq 9.4 \cdot 10^{-2}\, f_d \left(\frac{E_{\nu_\mu}}{\mathrm{TeV}} \right) \mathrm{km}^{-2}\, \mathrm{yr}^{-1} \ . \tag{19}$$

We have checked that radiation losses are irrelevant throughout the whole previous discussion.

Finally, taking into account that in the considered process the muon-neutrino and proton energies are related by $E_{\nu_\mu} \simeq 0.05\, E_p$, our prediction is

$$E_{\nu_\mu} \simeq 9.8\, \alpha\, \mathrm{TeV} \ , \tag{20}$$

and thanks Eqs. (19) and (8), the μ event rate in the detector is expected to be

$$\frac{dN^\oplus_{\mu}}{dA\, dt} \simeq 0.9\, f_d\, \alpha \ \mathrm{km}^{-2}\, \mathrm{yr}^{-1} \ . \tag{21}$$

4. Discussion and conclusions

So far, our attention has been restricted to the pion photo-production process (1). However, quite recently MILAGRO has discovered also a much harder gamma-ray emission of energy about 20 TeV from a region of about 3 degrees around Geminga [18)]. The origin of this emission is presently unclear, and it is natural to ask whether it can be due to the pion photo-production process (2) taking place inside the region $\mathcal{S}$. In order to settle this issue, we first note that the energy transferred from the proton to the pion is about $0.2\, E_p$, so that $E_\gamma \simeq 0.1\, E_p$. Hence, Eq. (8) entails

$$E_\gamma \simeq 19.5\, \alpha \ \mathrm{TeV} \ , \tag{22}$$

from which we see that these photons have *not* yet been detected. This circumstance sets an upper bound on the photon flux produced by process (2). It is straightforward to translate this limit into an upper bound on the flux of neutrinos arising from process (1). Assuming a E^{-2} photon spectrum, we find a flux consistent with the previous estimate within significant astrophysical uncertainties (like e.g. an electromagnetic cascade just outside $\mathcal{S}$).

Our conclusions support the hope that the signal detected by AMANDA-II towards Geminga might not be a statistical fluctuation and that neutrinos from Geminga can be discovered by the neutrino telescopes ICECUBE, ANTARES, NESTRO and NEMO. As a final remark, we note that if the gamma-ray flux observed by MILAGRO turns out to be due to an hadronic process possibly taking place around Geminga, an additional contribution to the neutrino flux from Geminga is naturally expected.

5. Acknowledgments

We are very grateful to Milla for the opportunity to present our result at this very stimulating Workshop. One of us (M. R.) wishes to thank Elisa Bernardini for several illuminating discussions on the topic considered in this paper.

6. References

1) T. Montaruli, Nucl. Phys. B (Proc. Suppl.) **165** (2007) 161.
2) G. F. Bignami and P. Caraveo, Ann. Rev. Astron. Astrophys. **34** (1996) 331.
3) J. Arens *et al.*, Nucl. Phys. B (Proc. Suppl.) **118** (2003) 388.
4) J. Carr, Nucl. Phys. B (Proc. Suppl.) **118** (2003) 383.
5) S. E. Tzamarias, Nucl. Instr. and Meth. A **502** (2003) 150.
6) E. Migneco, Nucl. Instr. and Meth. A (to appear).
7) R. Abbasi *et al.*, arXiv:0809.1646 (2008).
8) H. Yüksel, M. D. Kistler and T. Stanev, arXiv:0810.2784 (2008).
9) W. Bednarek, G. F. Burgio and T. Montaruli, arXiv:astro-ph/0404534 (2004).
10) B. Zhang, Z. G. Dai, P. Meszaros, E. Waxman and A. K. Harding, Astrophys. J. **595** (2003) 346.
11) B. Link and G. F. Burgio, Phys. Rev. Lett. **95** (2005) 181101.
12) P. Goldreich and W. H. Julian, Astrophys. J. **157** (1969) 869.
13) M. A. Ruderman and P. G. Sutherland, Astrophys. J. **196** (1975) 51.
14) K. S. Cheng, C. Ho and M. Ruderman, Astrophys. J. **300** (1986) 500.

15) P. A. Caraveo *et al.*, Science **301** (2003) 1345.
16) J. P. Halpern and M. Ruderman, Astrophys. J. **415** (1993) 286.
17) F. Halzen and D. Hooper, Rep. Progr. Phys. **65** (2002) 1025.
18) A. A. Abdo *et al.*, Astrophys. J. **664** (2007) L91.