High Energy Neutrinos from Astrophysical Sources

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Models of cosmological sources that may produce high energy neutrino fluxes detectable by planned high energy neutrino telescopes are reviewed. Implications to future detectors of model predictions, and of the model independent upper bound on high-energy neutrino fluxes implied by cosmic ray observations, are discussed.

1. Introduction and Summary

Large volume, high energy neutrino telescopes are being constructed to detect cosmologically distant neutrino sources [1]. The main motivation of a search for cosmological high-energy neutrino sources derives from the fact that the cosmic-ray energy spectrum extends to $> 10^{20}$eV and is most likely dominated above $\sim 10^{19}$eV by an extra-Galactic source of protons [2]. The dominance at the highest energy of an extra-Galactic source of protons is suggested by the flattening of the spectrum at $\sim 10^{19}$eV, combined with the lack of anisotropy and the evidence for a change in composition from heavy nuclei at lower energy to light nuclei (protons) at higher energy. High-energy neutrino production is likely to be associated with the production of high-energy protons, through the decay of charged pions produced by photo-meson interactions or inelastic nuclear collisions of the high-energy protons with the radiation field and the plasma in the vicinity of the source. Gamma-ray bursts (GRBs) [3] and active galactic nuclei (AGN) jets [4] have been suggested as possible sources of high-energy neutrinos that are associated with high-energy cosmic-rays.

The predicted neutrino fluxes may be detectable with planned high-energy neutrino telescopes. Detection of high energy cosmological neutrinos may allow to solve the puzzle of the unknown sources of ultra-high energy cosmic rays, and will provide stringent tests of GRB models. Furthermore, detection of high energy cosmic neutrinos will allow to test fundamental neutrino properties, such as coupling to gravity and flavor oscillations, with an accuracy many orders of magnitude better than is currently possible [5] (see §4).

In §2 we discuss the upper bound imposed by the observed cosmic ray flux at high energies on the high-energy neutrino flux produced in astronomical sources that are, like GRBs and the observed jets of AGN, of size not much larger than the proton $\gamma - p$ or $p - p(n)$ interaction mean-free-path [6]. The upper bound, which has come to be known in the literature as the Waxman-Bahcall (WB) bound, is shown in Figure 2 and implies that large volume, ~ 1 km^3, detectors are required to allow detection of astrophysical high energy neutrinos. The bound is robust and conservative, and can not be evaded by invoking magnetic fields or large hidden fluxes of extragalactic protons [6].

Two types of hypothetical high energy neutrino sources may exist, which may produce neutrino intensity exceeding the WB bound without violating the constraint imposed by cosmic ray observations. First, neutrinos could be produced in sources that are optically thick to photo-nucleon or nucleon-nucleon interactions. Second, the neutrinos could be produced by processes that do not give rise to high energy cosmic ray protons, such as the decay of dark matter particles, topological defects, superheavy relic neutrinos, or ultrahigh-energy photons [7]. The discussion of such hypothetical sources is beyond the scope of the present review.

In §3 we discuss the implications of the upper bound to AGN models of neutrino production. The models predict neutrino fluxes exceeding the bound by typically two orders of magnitude and therefore are not appropriate theoretical models upon which to base proposed observatories. The question of whether AGN jet models may be constructed to have a high photo-meson optical depth is also discussed in §3. High energy photon observations strongly constrain such models, implying that their predicted neutrino flux can not significantly exceed the WB bound.

Production of high energy neutrinos in GRBs is discussed in §4. The predicted flux of $\geq 10^{14}$eV neutrinos may be detectable by Cerenkov neutrino telescopes, e.g. AMANDA and ANTARES [1]. The flux above 10^{19} eV may be detectable by the Auger air-shower detector [8] and by planned space detectors [9]. The implications of GRB neutrino detection are also discussed in §4.

2. The WB bound

The high energy protons that produce neutrinos by $p-\gamma$ or by $p-p(n)$ interactions contribute to the observed cosmic ray flux after they leave the site where the neutrinos are created. Protons that are detected at earth with energies greater than 10^{18}eV must originate at redshifts $z < 1$, since they have maintained a high energy in spite of the possibility of interactions with the cosmic microwave background. The observed flux of high-energy cosmic rays determines therefore the local rate at which particles of those energies are being created. Fig. 1 shows a comparison of cosmic ray flux measurements with the predictions of a model where the cosmic ray generation rate in the nearby universe is

$$\left(E_{CR}^2 \frac{d\dot{N}_{CR}}{dE_{CR}}\right)_{z=0} = 10^{44}\text{erg Mpc}^{-3}\text{yr}^{-1}. \qquad (1)$$

It is possible that the energy generation rate given locally by Eq. (1) increases with redshift. In order to establish a conservative upper limit, one may assume that the local rate given in Eq. (1) evolves with redshift at the maximum rate observed for any astronomical population, i.e. the evolutionary rate exhibited by the quasars [10]. Knowing an upper limit to the universal proton production rate, given by Eq. (1) and the assumption of rapid redshift evolution[1], one can readily compute an upper limit to the rate of production of neutrinos by the same protons in sources of size not much exceeding the $p-p(n)$ or $p-\gamma$ interaction mean-free-path, by assuming that 100% of the energy of protons is lost to π^+ and π^0 and that the π^+ all decay to muons that also produce neutrinos [6]. This limit is shown in Figure 2.

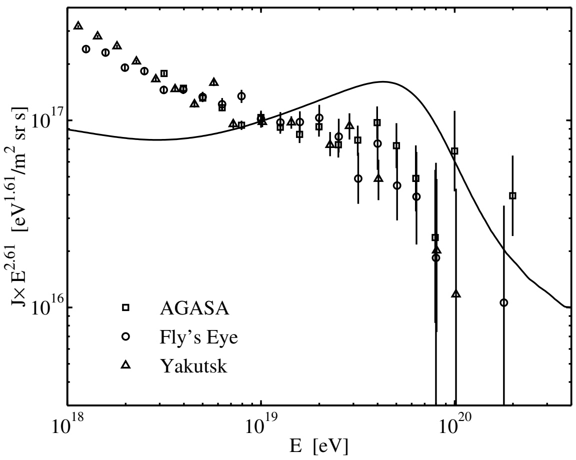

Figure 1. The observed high energy cosmic ray flux. Measurements are shown from the Fly's Eye, AGASA, and Yakutsk detectors [2]. The smooth curve is computed from Eq. (1).

Figure 1 shows that the smooth curve for the extragalactic proton cosmic ray flux, computed under the assumption that the generation rate of extragalactic protons is proportional to E^{-2}, falls below the total observed flux for energies less than 10^{19} eV. The assumed E^{-2} dependence is produced generically by the Fermi mechanism for accelerating high energy cosmic rays in shocks [13]. If, however, the lower energy cosmic rays were protons from extragalactic sources, then, as noted

[1]We note that Fig. 1 shows that the highest energy point measured by the AGASA experiment could be interpreted to suggest (with $\sim 1\sigma$ significance) that the cosmic ray generation rate at $E > 10^{20}$ eV is twice the rate obtained from our smooth curve generated by Eq. (1), implying that the upper bound might be underestimated by a factor of two at $\sim 10^{19}$ eV. However, the higher rate of generation is not observed by the Fly's Eye and Yakutsk experiments, and even if correct would imply only a small correction to the upper bound at this energy.

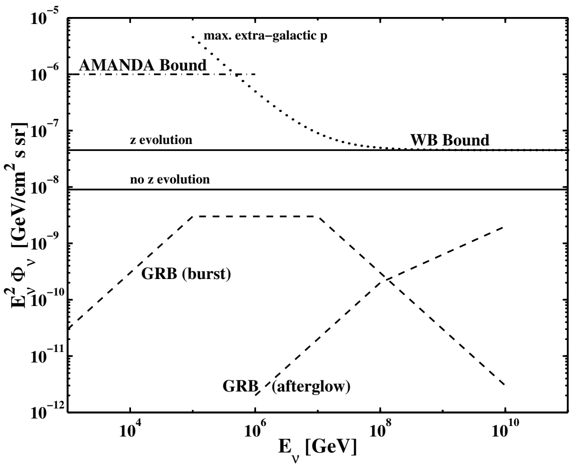

Figure 2. The WB upper bound on muon neutrino intensities ($\nu_\mu + \bar{\nu}_\mu$), adapted from [6]. The upper solid line gives the upper bound corrected for neutrino energy loss due to redshift and for the maximum known redshift evolution (QSO evolution). The lower solid line is obtained assuming no evolution. The dotted curve is the maximum contribution due to possible extra-galactic component of lower-energy, $< 10^{17}$ eV, protons. The dash-dot curve shows the experimental upper bound on diffuse neutrino flux recently established by the AMANDA experiment [11]. The dashed curves show the predictions of the GRB fireball model [5,12].

in [6], one could raise the upper bound for astrophysical neutrinos at these lower energies.

The observational evidence is that most of the observed cosmic rays in the energy range 10^{14} eV to 10^{17} eV are not protons [14] and therefore the total flux of cosmic rays cannot be used to raise the upper bound for neutrinos in the energy range 10^{14} eV to 10^{17} eV. Assuming, conservatively, that $\sim 10\%$ of the cosmic rays in this energy region are protons, the neutrino bound may be raised at energies $E_\nu < 10^{16}$ eV. Figure 2 illustrates with a curved dotted line the maximum contribution from unrecognized extragalactic sources of protons, i.e. sources of extragalactic protons that do not contribute significantly to the observed cosmic ray flux at 10^{19} eV.

Various ways that one might try to avoid the upper bound by invoking magnetic fields were discussed in [6]. It was shown that, given observational constraints, confinement of protons by magnetic fields surrounding the cosmic-ray sources or by large-scale structure fields can not affect the high-energy cosmic-ray flux, and therefore can not affect the neutrino bound. In particular, it was shown that even if large-scale structure fields are built to equipartition levels, protons of energy exceeding $\sim 10^{16.5}$ eV can not be confined to large-scale structures over a Hubble time. Large-scale structure magnetic fields can not therefore affect the WB bound at energy $\geq 10^{15}$ eV. Moreover, had proton confinement by large scale structure magnetic fields been possible, which might be the case for low energy protons, it would have most likely implied that the neutrino upper bound should be lower, rather than higher at $E_\nu \leq 10^{15}$ eV. This is due to the fact that confining high-energy cosmic-rays to high density regions would imply that the local cosmic-ray density is higher, rather than lower, than the universe average.

3. AGN Models

Figure 3 compares the WB upper bound to predictions by various models of photo-meson neutrino production in AGN jets. The previously published models are inconsistent with the cosmic ray limit; they typically predict fluxes one to two orders of magnitude above the bound.

The WB bound applies only to sources which are optically thin to photo-meson interactions. Previously published AGN jet models satisfy this requirement, due to the following constraint. The optical depth to photo-meson interactions for protons of energy E_p can be related to the optical depth for pair production of photons of much lower energy, E_γ. The threshold relation for photon-meson interactions is $E_p E_\gamma \approx m_\pi m_p$ and the threshold relation for pair production is $E'_\gamma E_\gamma = 2m_e^2$. Thus, a photon of energy E_γ that causes a photon-meson interaction with a proton of energy E_p could also pair-produce with a pho-

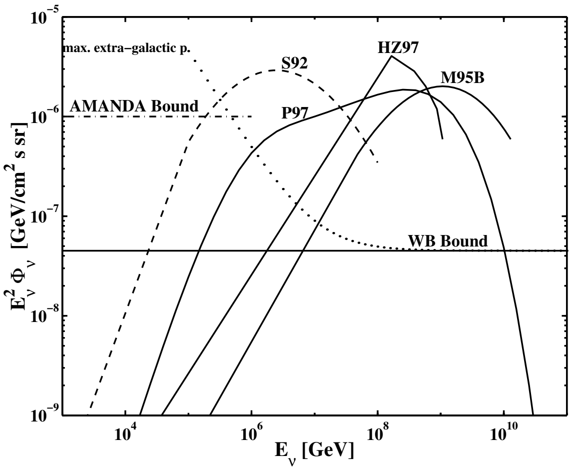

Figure 3. The WB upper bound on muon neutrino intensities ($\nu_\mu + \bar{\nu}_\mu$) (solid line) compared to predictions of representative AGN jet models, taken from the earlier papers of Mannheim (M95B), Protheroe (P97), and Halzen and Zas (HZ97) [4]. The AGN hidden-core conjecture (S92), to which the WB upper bound does not apply due to high photo-meson optical depth of the source, is taken from [15]. Note, that this conjecture is already ruled out by the AMANDA upper bound [11].

ton of energy $[2m_e^2/(m_\pi m_p)]E_p = 4 \times 10^{-6} E_p$. Taking account of the ratio between photo-meson and pair production cross sections, and of the fact that observed AGN photon energy distributions typically follow a power-law, $dn_\gamma/dE_\gamma \propto E_\gamma^{-2}$, one finds $\tau_{\gamma\gamma} \propto E_\gamma$ and [6]

$$\tau_{\gamma p}(E_p) \approx 2\tau_{\gamma\gamma}(E_\gamma = 10\text{GeV}) \left(\frac{E_p}{10^{19}\text{eV}}\right). \quad (2)$$

Emission of $\sim$ 1 TeV photons from "blazars," AGN jets nearly aligned with our line of sight, is now well established [16], and implies, as shown by Eq. (2), that the jet optical depth to photo-meson interaction is very small.

TeV emission is observed from the nearest blazars, which are hence relatively low-luminosity blazars. One may therefore argue, as recently done by Mannheim, Protherore and Rachen (MPR [17]), that the emission of high energy, $\sim$ 1 TeV, photons may be suppressed in high luminosity blazars, for which models with high optical depth may therefore be constructed. Making the *ad hoc* assumptions, that (i) The pair-production optical depth for high luminosity blazars (like 3C 279) exceeds unity for photons above 10 GeV, i.e. just above the highest energy for which data are available, and that (ii) The optical depth is due to ambient radiation (which is not detected) with a spectrum that deviates from a E_γ^{-2} power law, MPR concluded that the flux predicted by optically thick AGN models may exceed the WB bound by a factor ~ 2 at $\sim 10^{18}$ eV (see thick dashed curve in their figure 5a).

4. GRB Neutrinos

The widely accepted interpretation of the phenomenology of GRBs, bursts of 0.1 MeV–1 MeV photons lasting for a few seconds, is that the observable effects are due to the dissipation of the kinetic energy of a relativistically expanding wind, a "fireball," whose primal cause is not yet known [18]. The physical conditions in the fireball dissipation region allow Fermi shock acceleration of protons to energy $> 10^{20}$eV [19,20]. The average rate at which energy is emitted as γ-rays by GRBs is comparable to the energy generation rate of $> 10^{19}$ eV cosmic-rays given by Eq. (1) [19,3]. These two facts suggest that GRBs and ultra-high energy cosmic-rays have a common origin [3].

A burst of $\sim 10^{14}$eV neutrinos, accompanying observed γ-rays, is a natural consequence of the conventional fireball scenario [5]. The neutrinos are produced by π^+ created in interactions between fireball γ-rays and accelerated protons. The key relation is between the observed photon energy, E_γ, and the accelerated proton's energy, E_p, at the photo-meson threshold of the Δ-resonance. In the observer frame,

$$E_\gamma \, E_p = 0.2 \, \text{GeV}^2 \, \Gamma^2, \quad (3)$$

where phenomenologically the Lorentz factors of the expanding fireball are $\Gamma > 10^2$. For $\Gamma \approx 300$ and $E_\gamma = 1$ MeV, we see that characteristic proton energies $\sim 10^{16}$ eV are required to produce pions, leading to $\sim 10^{14}$ eV neutrinos.

The fraction $f_\pi(E_p)$ of proton energy lost to pion production is determined by the number density of photons at the dissipation region, and is given by [5]

$$f_\pi \approx 0.2\min(1, E_p/10^{16}\mathrm{eV})\frac{L_{\gamma,52}}{\Gamma_{2.5}^4\Delta t_{-2}}. \quad (4)$$

The γ-ray luminosity, the observed variability time and the wind Lorenz factor are normalized in Eq. (4) to their typical values inferred from observations, $L_\gamma = 10^{52}$erg/s, $\Delta t = 10^{-2}$s, and $\Gamma = 10^{2.5}$. Assuming that GRBs are the sources of observed ultra-high energy cosmic rays, i.e. that GRBs produce high energy protons at a rate given by Eq. (1), the intensity of high energy neutrinos implied by Eq. (4) is [5]

$$E_\nu^2\Phi_{\nu_x} \approx 10^{-9}\left(\frac{f_\pi}{0.2}\right)\min\left(1, \frac{E_\nu}{10^{14}\mathrm{eV}}\right)\frac{\mathrm{GeV}}{\mathrm{cm^2\,sr\,s}}. \quad (5)$$

ν_x stands for ν_μ, $\bar\nu_\mu$ and ν_e. The neutrino flux (5) is suppressed at high energy, $> 10^{16}$ eV, due to synchrotron energy loss of pions and muons [21,5].

High energy protons may also interact with 10 eV–1 keV photons produced on a time scale ~ 10 s following the GRB, due to interaction of the fireball with its surrounding medium. Inserting in Eq. (3) typical photon energy of ~ 100 eV, neutrinos of energy $\sim 10^{18}$ eV may be expected. The expected neutrino intensity due to this process is [12]

$$E_\nu^2\Phi_{\nu_x} \approx 10^{-10}\left(\frac{E_\nu}{10^{17}\mathrm{eV}}\right)^\alpha \frac{\mathrm{GeV}}{\mathrm{cm^2\,s\,sr}}, \quad (6)$$

where $\alpha = 1/2$ for $E_\nu > 10^{17}$eV and $\alpha = 1$ for $E_\nu < 10^{17}$eV. The neutrino flux is expected to be strongly suppressed at energy $> 10^{19}$ eV, since protons are not expected to be accelerated to energy $\gg 10^{20}$ eV.

The prediction of Eq. (6) is based on the assumption that the fireball expands into interstellar medium gas, with typical density $\sim 1\mathrm{cm}^{-3}$. This is expected, e.g., if the underlying progenitor is a binary neutron star merger. Some GRBs may result, however, from the collapse of a massive star, in which case the fireball is expected to expand into a pre-existing wind. The relevant plasma density is much higher in this case, $\sim 10^4\mathrm{cm}^{-3}$, implying a lower expansion Lorenz factor, higher proper photon density, and hence a larger fraction of proton energy lost to pion production. Protons of energy $E_p \geq 10^{18}$ eV lose all their energy to pion production in this case, and the expected neutrino intensity is [12,22]

$$E_\nu^2\Phi_{\nu_x} \approx 10^{-8}\min\left(1, \frac{E_\nu}{10^{17}\mathrm{eV}}\right)\frac{\mathrm{GeV}}{\mathrm{cm^2\,s\,sr}}. \quad (7)$$

The predicted intensity of 10^{14} eV neutrinos produced by photo-meson interactions with observed 1 MeV photons, Eq. (5), implies a detection of ~ 10 neutrino induced muons per year in planned 1km^3 Cerenkov neutrino detectors, correlated in time and direction with GRBs. The predicted intensity of 10^{17} eV neutrinos, produced by photo-meson interactions during the onset of fireball interaction with its surrounding medium in the case of fireball expansion into a pre-existing wind, Eq. (7), implies a detection of several neutrino induced muons per year in a 1km^3 detector. In this case, the predicted flux of 10^{19} neutrinos may also be detectable by planned large air-shower detectors [8,9].

Inelastic p-n collisions may produce ~ 10 GeV neutrinos with a fluence of $\sim 10^{-4}\mathrm{cm}^{-2}$ per burst, due to either p-n decoupling in a wind with high neutron fraction and high, > 400, Lorentz factor, or to neutron diffusion in a wind with, e.g., strong deviation from spherical symmetry [23]. The predicted number of events in a 1km^3 detector is $\sim 10\mathrm{yr}^{-1}$. Their detection will, however, be difficult, since at ~ 10 GeV the effective volume of planned detectors is much smaller than 1km^3.

Detection of high energy neutrinos will test the shock acceleration mechanism and the suggestion that GRBs are the sources of ultra-high energy protons, since $\geq 10^{14}$ eV ($\geq 10^{18}$ eV) neutrino production requires protons of energy $\geq 10^{16}$ eV ($\geq 10^{19}$ eV). The dependence of $\sim 10^{14}$ eV neutrino flux on wind Lorentz factor, Eq. (4), and the dependence of $\sim 10^{17}$ eV neutrino flux on fireball environment, imply that the detection of high energy neutrinos will also provide constraints on wind Lorentz factor [24], and on the GRB progenitor.

Detection of GRB neutrinos could be used to test the simultaneity of neutrino and photon arrival to an accuracy of ~ 1 s (~ 1 ms for short bursts), checking the assumption of special relativity that photons and neutrinos have the same limiting speed, and the weak equivalence principle, according to which photons and neutrinos should suffer the same time delay as they pass through a gravitational potential. With 1 s accuracy, a burst at 100 Mpc would reveal a fractional difference in limiting speed of 10^{-16}, and a fractional difference in gravitational time delay of order 10^{-6} (considering the Galactic potential alone), many orders of magnitude better than present limits based on supernova 1987A [25].

The model discussed above predicts the production of high energy muon and electron neutrinos. However, if the atmospheric neutrino anomaly has the explanation it is usually given, oscillation to ν_τ's with mass ~ 0.1 eV [26], then one should detect equal numbers of ν_μ's and ν_τ's. Up-going τ's, rather than μ's, would be a distinctive signature of such oscillations. Since ν_τ's are not expected to be produced in the fireball, looking for τ's would be an "appearance experiment." Due to the cosmological distance of GRB sources, flavor change will take place for Δm^2 as low as $\Delta m^2 \geq 10^{-16}\mathrm{eV}^2$.

REFERENCES

1. Halzen, F. 1999, in 17th Intl. Workshop on Weak Interactions and neutrinos, Cape Town, South Africa (astro-ph/9904216).
2. Nagano, M. & Watson, A. A., Rev. Mod. Phys. **72**, 689 (2000).
3. Waxman, E., Physica Scripta **T85**, 117 (2000); Waxman, E., Nucl. Phys. B (Proc. Suppl.) **87**, 345 (2000).
4. K. Mannheim, Astropar. Phys. **3**, 295 (1995); F. Halzen and E. Zas, Astrophys. J. **488**, 669 (1997); R. J. Protheroe, Adelaide preprint ADP-AT-96-4 (astro-ph/9607165).
5. Waxman, E., & Bahcall, J. N., Phys. Rev. Lett. **78**, 2292 (1997).
6. Waxman, E., & Bahcall, J. N., Phys. Rev. **D59**, 023002 (1999); Waxman, E., & Bahcall, J. N., Submitted to Phys. Rev. D (astro-ph/9902383).
7. P. Bhattacharjee and G. Sigl, Phys. Reports, 327, 109 (2000).
8. J. Capelle, J. W. Cronin, G. Parente, and E. Zas, Astropart. Phys. **8**, 321 (1998).
9. J. Linsley, MASS/AIRWATCH Huntsville workshop report, pp. 34–74 (1995).
10. B. J. Boyle and R. J. Terlevich, Mon. Not. Roy. Astron. Soc. **293**, L49 (1998).
11. E. Anderws *et al.*, astro-ph/0009242 (2000).
12. Waxman, E., & Bahcall, J. N., Ap. J. **541**, 707 (2000).
13. A. R. Bell, MNRAS **182**, 147 (1978); R. D. Blandford, J. P. Ostriker, Ap. J. **221**, L29 (1978) .
14. T. H. Burnett *et al.* (the JACEE collaboration), Astrophys. J. **349**, L25 (1990); K. Bernlohr *et al.*, Astropart. Phys. **8**, 253 (1998); B. R. Dawson, R. Meyhandan, K. M. Simpson, Astropart. Phys. **9**, 331 (1998).
15. F. Stecker, C. Done, M. Salamon, and P. Sommers, Phys. Rev. Lett. **69**, 2738 (1992).
16. M. Punch *et al.* Nature **358**, 477 (1992); J. Quinn *et al.* Astrophys. J. **456**, L83 (1996).
17. K. Mannheim, R.J. Protheroe, and J.P. Rachen, submitted to Phys. Rev. D (astro-ph/9812398, v1,v2, and v3).
18. Piran, T., Phys. Rep. **314**, 575 (1999).
19. Waxman, E., Phys. Rev. Lett. **75**, 386 (1995).
20. Vietri, M., Ap. J. **453**, 883 (1995); Milgrom, M. & Usov, V., Ap. J. **449**, L37 (1995).
21. Rachen, J. P., & Mészáros, P., Phys. Rev. **D58**, 123005 (1998).
22. Dai, Z. G., & Lu, T., submitted to Ap. J. (astro-ph/0002430).
23. Derishev, E. V., Kocharovsky, V. V., & Kocharovsky, Vl. V, Ap. J. **521**, 640 (1999); Bahcall, J. N., & Mészáros, Phys. Rev. Lett., 85, 1362 (2000); Mészáros, P., & Rees, M., Ap. J., submitted (astro-ph/0007102).
24. Alvarez-Muniz, J., Halzen, F., & Hooper, D. W., Phys. Rev. **D62**, 093015 (2000).
25. Bahcall, J. N., *Neutrino Astrophysics*, Cambridge University Press (NY 1989).
26. Fukuda, Y., *et al.*, Phys. Lett. **B335**, 237 (1994); Casper, D., *et al.*, Phys. Rev. Lett. **66**, 2561 (1991); Fogli, G. L., & Lisi, E., Phys. Rev. **D52**, 2775 (1995).