PeV neutrinos observed by IceCube from cores of active galactic nuclei

Floyd W. Stecker*

NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA
(Received 3 June 2013; published 15 August 2013)

I show that the high energy neutrino flux predicted to arise from active galactic nuclei cores can explain the PeV neutrinos detected by IceCube without conflicting with the constraints from the observed extragalactic cosmic-ray and γ-ray backgrounds.

Recently, the IceCube Collaboration has reported the first observation of cosmic 2 PeV energy neutrinos giving a signal $\sim 3\sigma$ above the atmospheric background [1]. More recently, 18 events $\sim 4\sigma$ above the expected atmospheric background were reported with energies above 100 TeV. These neutrinos are likely to be of cosmic origin; their angular distribution is consistent with isotropy. The average spectral index for these neutrinos was approximately -2 over the energy range between ~ 100 TeV and 2 PeV [2].

In 1991 we proposed a model suggesting that very high energy neutrinos could be produced in the cores of active galaxies (AGN) such as Seyfert galaxies [3]. Using that model, we gave estimates of the flux and spectrum of high energy neutrinos to be expected. In light of subsequent AGN observations and the discovery of neutrino oscillations, the flux estimates for this model were revised downward [4], although the shape of the predicted neutrino spectrum remained unchanged.

The new estimate was obtained by lowering the flux shown in the figure in Ref. [5] by a factor of 20. This rescaling gives a value for the ν_μ flux at 100 TeV of $E_\nu^2 \Phi(E_\nu) \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} and a flux of $\sim 5.6 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} at ~ 1 PeV. The peak flux in these units occurs at an energy ~ 1 PeV.

In our model protons are accelerated by shocks in the cores of AGN in the vicinity of the black hole accretion disk (see, e.g., Ref. [6]). Being trapped by the magnetic field, they lose energy dramatically by interactions with the dense photon field of the "big blue bump" of thermal emission from the accretion disk (see, e.g., Ref. [7]) which is optically thick to protons [3]. The primary interactions are those from photomeson production. The primary neutrino producing channel, which occurs near threshold, is

$$\gamma + p \rightarrow \Delta^+ \rightarrow n + \pi^+, \qquad (1)$$

giving the pion an energy roughly ≈ 0.2 of that of the emitting protons [8]. Since the secondary γ rays from $\Delta^+ \rightarrow p + \pi^0$ followed by $\pi^0 \rightarrow 2\gamma$ lose energy in the source from electron-positron pair production and the protons in our model do not reach ultrahigh energies,

losing energy in the source, there is no conflict with ultrahigh energy cosmic-ray (UHECR) or extragalactic γ-ray background constraints [9]. Full details of the model may be found in Refs. [3,4] and references therein.

The important decays leading to ν production are $\pi^+ \rightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$, with all leptons carrying off about $1/4$ of the pion energy. Thus in our model we expect that with an assumed power-law proton spectrum from shock acceleration, followed by photomeson production, there will be both more and higher energy ν_e's produced than $\bar{\nu}_e$'s, reducing the effect of Glashow resonance production at 6.3 PeV [10] in the detector (see also Ref. [9]).

Given the effective area of IceCube for an isotropic flux of ν_e's at ~ 1 PeV of 5 m^2 and an exposure time of 615.9 days [1], and giving a total predicted ν flux at ~ 1 PeV of $\sim 6 \times 10^{-14}$ (cm^2 s sr)$^{-1}$, we would predict that IceCube should see a total of ~ 6 neutrino induced events.

The main uncertainty in the magnitude of the modeled flux is from the uncertainty in the number of AGN per Mpc^3. The neutrino spectrum was predicted to be proportional to $E^{-2.1}$ between 1 and 10 PeV under the assumption that the proton spectrum has an E^{-2} dependence from shock acceleration. The average slope of the neutrino spectrum was predicted to be -3.1 between 1 and 100 PeV. Protons were assumed to be accelerated up to a maximum energy of 2.5×10^4 PeV. It is, of course, possible that the average proton spectrum can be steeper than E^{-2} and that the maximum energy to which protons are accelerated is less than 2.5×10^4 PeV. Since the sources are extragalactic, we expect that the observed neutrinos will have a roughly isotropic angular distribution on the sky.

Given the uncertainties in the model parameters, the general agreement with the AGN core model is significant, particularly the prediction of a peak neutrino energy flux at ~ 1 PeV. I conclude that, given the present IceCube results, AGN cores may naturally account for the implied ν flux and angular distribution without violating constraints from γ-ray background and UHECR fluxes. More IceCube data should soon be forthcoming.

*Floyd.W.Stecker@nasa.gov

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