Neutrino Flux from Cosmic Ray Accelerators in the Cygnus Spiral Arm of the Galaxy

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(Dated: December 2006)

Intriguing evidence has been accumulating for the production of cosmic rays in the Cygnus region of the Galactic plane. We here show that the IceCube experiment can produce incontrovertible evidence for cosmic ray acceleration by observing the neutrinos from the decay of charged pions accompanying the TeV photon flux observed in the HEGRA, Whipple, Tibet and Milagro experiments. Our assumption is that the TeV photons observed are the decay products of neutral pions produced by cosmic ray accelerators in the nearby spiral arm of the galaxy. Because of the proximity of the sources, IceCube will obtain evidence at the 5σ level in 15 years of observation.

Evidence may be emerging for a cosmic accelerator in the Cygnus spiral arm. The observation of the Cygnus region by the HEGRA IACT-system has allowed the serendipitous discovery of a TeV γ-ray source [1], with an average flux ∼ 3% of the Crab Nebula [2]. The analysis of the total 278.3 hours of observations performed in two periods from 1999 to 2002 (120.5 hours from 1999 to 2001 [1] and 157.8 hours during 2002 [3]) has revealed the presence of a steady (and possibly extended) TeV source, with hard injection spectrum.

The excess significance of the TeV source is 7.1σ and it appears extended at more than 4σ level with a morphology which is suitably described by a Gaussian profile. The source is termed TeV J2032+4130 after the position of the center of gravity and its extension (Gaussian 1σ radius) is 6.2′(±1.2′stat ± 0.9′sys). Especially intriguing is the possible association of TeV J2032+4130 with Cygnus OB2, a cluster of more than 2700 (identified) young, hot stars with a total mass of ∼ 104 solar masses [4]. At a relatively small distance (∼ 5000 light years) to Earth [5], this is the largest massive Galactic stellar association.

The observed hot spot has no clear counterpart and the spectrum is not easily accommodated with synchrotron radiation by electrons. The difficulty to accommodate the spectrum by conventional electromagnetic mechanisms has been exacerbated by the failure of CHANDRA and VLA to detect X-rays or radio waves signaling acceleration of any electrons [6]. The two most plausible models to explain the γ-ray signal are: (a) A proton beam (accelerated in the stellar winds of Cygnus OB2 [1, 6], or else in the wind nebulae of an undetected nearby pulsar [2]) interacting with a molecular cloud to produce pions that are the source of the gamma rays. Proton acceleration to explain the TeV photon signal requires only 1% efficiency for the conversion of the energy in the stellar wind into cosmic ray acceleration. (b) The TeV gamma rays can also originate in the photo-deexcitation of ultra-relativistic nuclei (Lorentz factor ≈ 106) that are themselves the photo-disintegration products of heavier nuclei broken-up in the bath of intense UV photons from the Lyman α emissions of hot stars [8]. As in the proton beam model, the required power density for acceleration of nuclei is 2 orders of magnitude smaller than the kinetic energy budget of the entire association.

Another set of observations performed during 1989-1990 by the Whipple Observatory [7] has been recently reanalyzed in the light of the HEGRA data. These confirm an excess in the same direction as J2032+4130, although with considerably larger average flux (∼ 12% of the Crab), above a peak energy response of 0.6 TeV. The statistical significance of the signal is only 10% smaller with selection of events above 1.2 TeV. However, the large differences between the flux levels cannot be explained as errors in estimation of the sensitivity of the experiments since they have been calibrated by the simultaneous observations of other TeV sources. More recently, data taken with the Whipple Observatory during 2003-2005 have been reported [10]. The analysis of the latest dataset reveals a TeV hot spot (integral flux ∼ 8% of the Crab) that is displaced about 9 arcminutes to the northeast of the TeV J2032+4130 position. A re-analysis [11] of a 10-hour VLA mosaic exposure towards TeV J2032+4130 (based on the alternative source hypothesis) allowed the detection of a weak, predominantly non-thermal, shell-like supernova remnant-type object (with location and morphology very similar to the HEGRA source) that can be the cosmic ray engine powering the OB association.

Very recently, the Milagro Collaboration reported an excess of events from the Cygnus region at the 10.9σ level [12]. The observed flux within a 3° × 3° window centered at the HEGRA source is 70% of the Crab at the median detected energy of 12 TeV, and has a differential spectrum ∝ E−2.8. Such a flux largely exceeds the one reported by the HEGRA Collaboration, implying that there could be a population of unresolved TeV γ-ray sources within the Cygnus OB2 association.

The Milagro Collaboration also reported a new hot spot, christened MGRO J2019+37, at right ascension = 304.83° ± 0.14°stat ± 0.3°sys and declination = 36.83° ± 0.08°stat ± 0.2°sys [12]. This new unidentified source is observed with statistical significance > 6σ above the average diffuse γ-ray emission in the region. A fit to a circular 2-dimensional Gaussian yields a width of 0.32±0.12...
degrees, which for a distance of 1.7 kpc suggests a source radius of about 9 pc. For a differential spectrum $\propto E^{-2.0}$, the brightest hotspot in the Milagro map of the Cygnus region represents a flux of 1 Crab above 12.5 TeV. Interestingly, the Tibet AS-gamma Collaboration has observed a cosmic ray anisotropy from the direction of Cygnus, which is consistent with Milagro’s measurements. Unfortunately, the Tibet array has very little power to distinguish how much of the anisotropy should be attributed to $\gamma$-rays and how much, if any, to baryons.

The brightest Milagro hot spot is located outside the OB association. However, the $\gamma$-ray signal is found to trace the gas density distribution in the region. The model proposed is that of a cosmic ray beam, perhaps powered by a millisecond pulsar, which interacts with a molecular cloud positioned a few degrees to the southeast of the OB star cluster. If the $\gamma$-ray emission from MGRO J2019+37 originates in $\pi^0$ decay, it is necessarily accompanied by a flux of high energy neutrinos emerging from the $\pi^\pm$ population. In this paper we discuss in detail the prospects to observe such a flux with the IceCube neutrino telescope.

The pion spectrum resulting from collisions of the ultrarelativistic protons on the molecular cloud is expected to obey a modified Feynman scaling in the central rapidity region, $dN_{\pi}/dE_{\pi}|_{E_{\pi}} \approx C(E_{\pi})/E_{\pi}$, where $C$ may be growing as some power of $\ln E_{\pi}$. For given $E_{\pi} < 0.08 E_{\pi,\text{max}}$, we may convolve with a proton spectrum typical of Fermi engines, $dN_p/dE_p \propto E_p^{-1}$, to obtain the pion spectrum where $C(E_{\pi})$ is generically a function which grows as a power of $\ln E_{\pi}$, falling to zero at the cutoff $E_{\pi} = 0.08 E_{\pi,\text{max}}$. Since $\pi^0$'s, $\pi^+$'s, and $\pi^-$'s are made in equal numbers, one expects two photons, two $\nu^+$'s, and four $\nu^-$'s per $\pi^0$. Gamma rays, produced via $\pi^0$ decay carry one-half of the energy of the pion. Each $\pi^-$ decays to 3 neutrinos and an electron, $\pi^- \rightarrow \mu^- \nu_\mu \bar{\nu}_e e^-$. The electron radiatively cools through interactions with the gas and the ambient magnetic and radiation fields. Typically $e^-$ synchrotron emission extends from radio frequencies to X-rays. The average neutrino energy from the direct pion decay is $\langle E_{\nu_\mu} \rangle_{\pi} = (1 - r) E_{\pi}/2 \approx 0.22 E_{\pi}$ and that of the muon is $\langle E_{\nu_\mu} \rangle_{\mu} = (1 + r) E_{\pi}/2 \approx 0.78 E_{\pi}$, where $r$ is the ratio of muon to the pion mass squared. Now, taking the $\nu_\mu$ from muon decay to have $1/3$ the energy of the muon, the average energy of the $\nu_\mu$ from muon decay is $\langle E_{\nu_\mu} \rangle_{\mu} = (1 + r) E_{\pi}/6 = 0.26 E_{\pi}$. Similar considerations apply for the charged conjugate process. For simplicity, hereafter we consider that all neutrinos carry one quarter of the energy of the pion. The energy-bins $dE$ scale with these fractions, and we arrive at

$$
\frac{dN_{\gamma}}{dE_{\gamma}}(E_{\gamma} = E_{\pi}/2) = 4 \frac{dN_{\pi}}{dE_{\pi}}(E_{\pi}),
$$

$$
\frac{dN_{\nu_\mu}}{dE_{\nu_\mu}}(E_{\nu_\mu} = E_{\pi}/4) = 8 \frac{dN_{\pi}}{dE_{\pi}}(E_{\pi}),
$$

$$
\frac{dN_{\nu_e}}{dE_{\nu_e}}(E_{\nu_e} = E_{\pi}/4) = 16 \frac{dN_{\pi}}{dE_{\pi}}(E_{\pi}),
$$

where $\pi$ denotes any one of the three pion charge-states.

Whereas the details are complex and predictions can be treacherous, it is clear that the astrophysical ambiguities far outweigh the details associated with the particle physics, and hence it is safe to assume that identical fluxes of $\gamma$-rays and $\nu_\mu$ are produced. Terrestrial experiments have shown that $\nu_\mu$ and $\nu_\tau$ are maximally mixed with a mass-squared difference $\sim 10^{-3}$ eV$^2$, and that $|\langle \nu_\mu | \nu_\tau \rangle|^2$ is nearly zero. Here $\nu_3 \simeq (\nu_\mu + \nu_\tau)/\sqrt{2}$ is the third neutrino eigenstate. This implies that any initial flavor ratio having $\omega_e = 1/3$ will arrive at Earth with ratios $\omega_\nu : \omega_\mu : \omega_\tau = 1 : 1 : 1$. Thus, there is a fairly robust prediction that the initial flavor ratios of $1 : 2 : 0$ given in Eq. (3) would arrive at Earth democratically distributed, i.e., $1 : 1 : 1$. From these remarks, one finds a nearly identical flux,

$$
\frac{dF_{\nu_\alpha}}{dE_{\nu_\alpha}} = \frac{1}{4\pi d^2} \frac{dN_{\nu_\alpha}}{dE_{\nu_\alpha}} \approx 7.7 \times 10^{-12} \left( \frac{E_{\nu_\alpha}}{\text{TeV}} \right)^{-2.6} \text{ TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}
$$

for each of the three neutrino flavors $\alpha = e, \mu, \tau$.

The Antarctic Muon And Neutrino Detector Array (AMANDA) uses natural 1 mile deep Antarctic ice as a Cerenkov detector, has operated for more than 5 years in its final configuration: 19 strings instrumented with 680 optical modules. IceCube, the successor experiment to AMANDA, is now under construction. It will consist of 80 kilometer-length strings, each instrumented with 60 digital optical modules (DOM) spaced by 17 m. The deepest module is 2.4 km below the surface. The strings are arranged at the apexes of equilateral triangles 125 m on a side. The instrumented (not effective!) detector volume is a full cubic kilometer. A surface air shower detector, IceTop, consisting of 160 Čerenkov detectors deployed over 1 km$^2$ above IceCube, augments the deep-ice component by providing a tool for calibration, background rejection and air-shower physics. The angular resolution for muon tracks $\sim 0.7^\circ$ allows a search window of $1^\circ \times 1^\circ$. Construction of the detector started in the Austral summer of 2004/2005 and will continue for 6 years, possibly less. At the time of writing, data collection by the first 22 strings and 52 IceTop stations has begun.

The event rate from a source located at given declination can be calculated from the knowledge of the so-called neutrino effective area. This parameter strongly depends on the energy due to the almost linear increase of the
an event rate of muon neutrinos with

Using the neutrino flux given in Eq. (3) and convolving the muon neutrino event rate from the Cygnus region configuration. IceCube and the effective area of AMANDA II is also shown.

Such an effective area is shown in Fig. 1 together with the trigger level effective area (defined as 8 DOM threshold) of IceCube and the effective area of the AMANDA final configuration.

Equipped with the effective area shown in Fig. 1 it is straightforward to calculate lower and upper limits on the muon neutrino event rate from the Cygnus region

Using the neutrino flux given in Eq. (4) and convolving it with the IceCube neutrino effective area we foresee an event rate of muon neutrinos with $E_\nu > 1$ TeV of $1.1 \, \text{yr}^{-1} < dN_\mu/dt < 4.1 \, \text{yr}^{-1}$. The energy distribution of such events is shown in Fig. 2.

We now turn to the estimate of the background. For the atmospheric neutrino flux, arising from the decay of pions and kaons produced in cosmic ray interactions with the air molecules, we adopt the estimates of Ref. [22]. We obtain the number of expected muon tracks from atmospheric neutrinos as in Eq. (4), using the $\nu_\mu$, atmospheric neutrino flux integrated over a solid angle of $1^\circ \times 1^\circ$ width around the direction of the MGRO J2019+37 (zenith angle $\theta = 53.2^\circ$). We obtain an expected background of atmospheric tracks, $1.2 \, \text{yr}^{-1} < dN_B/dt < 5.5 \, \text{yr}^{-1}$.

These event rates are based on a conservative estimate of the level of detail to which we currently understand the detector performance. However, since this understanding will improve over time one expects the systematic errors to decrease to the levels projected in the baseline design reported in [20]. Therefore, to determine the discovery reach we employ the semianalytical calculation presented in [24] based on a full Monte Carlo simulation using these projected baseline detector properties, with quality cuts referred as level 2 cuts [20]. For a muon energy threshold of 100 GeV and minimum track length of 300 m, the expected rate of $\nu_\mu$ induced tracks is $dN_\mu/dt \simeq 3 \, \text{yr}^{-1}$, with a background of $dN_B/dt \simeq 2.5 \, \text{yr}^{-1}$. Hence, after 15 yr of operation, the (total) detection significance,

$$S_{\text{det}} = \frac{N_\mu}{\sqrt{N_B + N_\mu}} \simeq 5\sigma,$$

is expected to be at discovery level.

We now verify that our results are consistent with existing data. Very recently, the AMANDA II data collected during 2000 - 2004 (with a lifetime of 1001 days) was analyzed to set new limits on the neutrino fluxes from point sources (circular bin size varying between 2.25$^\circ$ and 3.75$^\circ$ depending on declination) [23]. For the effective area shown in Fig. 1 the expected background from atmospheric neutrinos ($E_\nu > 100$ GeV) in a $1^\circ \times 1^\circ$ window is $dN_B/dt \simeq 0.22 \, \text{yr}^{-1}$. The AMANDA Collaboration reported an expected atmospheric neutrino background from the direction of J2032+4130 of 6.8 events, in complete agreement with our calculations. The experiment observed 7 events pointing towards the same direction of

FIG. 1: The IceCube effective area for muon track reconstruction as a function of the neutrino energy. Two curves are shown indicating the trigger level and the recent estimate with very conservative quality cuts. For comparison the effective area of AMANDA II is also shown.

FIG. 2: Differential energy distribution of event rates from MGRO J2019+37. The different curves indicate rates computed using the effective area (a) of the trigger level condition, (b) of the conservative quality cuts, (c) of the AMANDA II array.
the sky, leading to a 90\% CL upper limit,

\[ E_\nu^2 \frac{dF_\nu}{dE_\nu} = 1.1 \times 10^{-10} \text{ TeV cm}^{-2} \text{s}^{-1}. \]  

(6)

Thus, the sensitivity reach at AMANDA cannot probe the predicted flux given in Eq. (3).

In summary, by observing the neutrinos from the decay of charged pions accompanying the recently detected γ-rays with the Milagro experiment, the IceCube neutrino telescope will produce incontrovertible evidence for cosmic ray acceleration in the Cygnus spiral arm. In this paper, we have discussed in detail the sensitivity reach of IceCube to the brightest hot spot, MGRO J2019+37. Contributions from TeV γ-ray hot spots (still hidden) within the Cygnus OB2 association will certainly enhance the signal [27]. Moreover, as suggested recently by the Milagro Collaboration [12], to smoothly match EGRET data in the 100 MeV energy region, the spectra by the Milagro Collaboration [12], to smoothly match EGRET data in the 100 MeV energy region, the spectra from all the sources in the Cygnus region should have a break (perhaps because of absorption effects) and be harder than \( E^{-2.6} \) at lower energies. As an illustration, we have estimated the expected event rate from MGRO J2019+37, using the semianalytical calculation given in [24] and assuming a spectrum \( \propto E_\nu^{-2.4} \),

\[ dN_\nu/dt \simeq 9.0 \text{ yr}^{-1}. \]  

(7)

For a background of 2.5 yr\(^{-1} \) events, this implies that IceCube will attain a 5σ discovery reach in 2 years of operation!

Acknowledgments

We would like to thank Juande Zornoza for deriving the effective areas shown in Fig. 1. This work has been supported in part by the US NSF under Grant No. OPP-0236449, in part by the US Department of Energy (DoE) Grant No. DE-FG02-95ER40896, in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, and in part by the University of Wisconsin-Milwaukee.

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