Prospects of Identifying the Sources of the Galactic Cosmic Rays with IceCube

Alexander Kappes [a,*,1], Francis Halzen [a], Aongus Ó Murchadha [a]
[a] *Department of Physics, University of Wisconsin, Madison, WI 53706, USA*

Abstract

The Milagro detector has identified several TeV γ-ray sources with fluxes consistent with typical comsic-ray generating supernova remnants interacting with the interstellar medium. In this contribution we show that IceCube, a kilometer-scale neutrino detector under construction at the South Pole, can provide incontrovertible evidence of cosmic-ray acceleration in these sources by detecting neutrinos. The sensitivity is maximal if only events with energies above about 40 TeV are considered where the atmospheric neutrino background is largely reduced.

Key words: Neutrino telescopes, IceCube, Galactic γ-ray sources, Milagro hotspots, Pevatrons
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1. Gamma-ray observations

It is believed that Galactic accelerators are powered by the conversion of 10^{50} erg of energy into particle acceleration by diffusive shocks associated with young (1000–10,000 year old) supernova remnants expanding into the interstellar medium (Drury et al., 1994). The cosmic rays will interact with atoms in the interstellar medium producing pions that decay into photons and neutrinos. Dense molecular clouds, often found in star forming regions where the supernovae explosions occur, are particularly efficient at converting protons into pions that decay into 'pionic' gamma rays and neutrinos. Unlike the remnants seen alone, there is no electromagnetic contribution to the TeV radiation that is difficult to differentiate from the pionic gamma rays. The existence of the 'knee' in the cosmic-ray spectrum tells us that there must exist Galactic cosmic-ray sources producing protons with energies of several PeV. These 'Pevatrons' will produce pionic gamma rays with spectra extending up to several hundred TeV without cut-off. By straightforward energetics arguments such sources must emerge in global sky surveys with the sensitivity of the Milagro experiment (Milagro Coll. et al., 2007a). We will argue that one Pevatron, MGRO J1908+06, has likely been identified.

To date, the Milagro collaboration has identified eight Galactic sources of high-energy gamma rays. On the basis of prior observations some of these sources appear to correspond to objects unlikely to be significant sources of the Galactic cosmic rays. For example, three Milagro hotspots are at the same locations as the Crab nebula, Geminga, and the Boomerang nebula. As these objects are known to be pulsar-wind nebulae, and therefore not likely to be significant proton accelerators, we do not consider them in the context of this study. Three of these sources, MGRO J1908+06, MGRO J2019+37, and MGRO J2031+41, have post-trial significances

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[*] Corresponding author.
Email address: `kappes@icecube.wisc.edu` (Alexander Kappes).

[1] on leave of absence from Universität Erlangen-Nürnberg, Physikalisches Institut, D-91058, Erlangen, Germany.

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of $\geq 4.9\,\sigma$ (Milagro Coll. et al., 2007b). The remaining two hotspots—candidate sources C1 (MGRO J2043+36) and C2 (MGRO J2032+37)—are located within the Cygnus region of the Galaxy at Galactic longitudes of 77° and 76°, respectively. Another potential hotspot, MGRO J1852+01, falls currently somewhat below the threshold set by the Milagro collaboration for candidate sources. If confirmed it will be the strongest source in Milagro's entire sky map with a flux about 2.5 times higher than MGRO J2019+37 (Abdo, 2007). In the analysis that follows, we will consider the five identified Milagro hotspots together with MGRO J1852+01 as our candidate cosmic-ray accelerators.

We focus in particular on MGRO J1908+06. The H.E.S.S. observations of this source reveal a spectrum consistent with a E^{-2} dependence from 500 GeV to 20 TeV without evidence for a cut-off (H.E.S.S. Coll. et al., 2007). In a follow-up analysis (Milagro Coll. et al., 2008) the Milagro collaboration showed that its own data are consistent with an extension of the H.E.S.S. spectrum to at least 90 TeV (Fig. 1). This is suggestive of pionic gamma rays from a Pevatron whose cosmic-ray beam extends to the 'knee' in the cosmic-ray spectrum at PeV energies. Another source with a measured spectrum consistent with E^{-2} is MGRO J2031+41 MAGIC Coll. et al. (2008). The lower flux measured by MAGIC can be attributed to the problem of background estimation for Cherenkov telescopes in a high density environment like the Cygnus region.

Not all sources have known lower-energy counterparts, however. Although the H.E.S.S. telescope array discovered a GeV-TeV counterpart to MGRO J1908+06 and MAGIC to MGRO J2031+41, the VERITAS telescopes failed to detect an excess at the location of the source MGRO J2019+37 (VERITAS Coll. et al., 2007). A possible reason for this distinction is that this source, located in the Cygnus region of the Galaxy, may not be the accelerator but a nearby molecular cloud illuminated by a Pevatron beam. While the pionic gamma ray spectrum extends to hundreds of TeV, it is expected to be suppressed in the TeV search window of VERITAS (Gabici and Aharonian, 2007). Indeed, there could be many potential accelerators in the Cygnus region, one of the principal star-forming areas of the Galaxy.

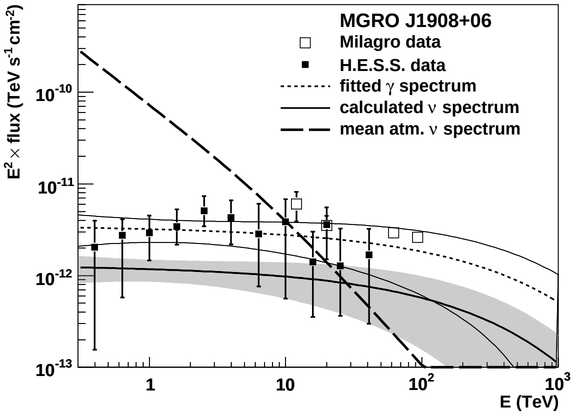

Fig. 1. The γ-ray and neutrino fluxes from MGRO J1908+06. The shaded regions surrounding the fluxes represent the range in the spectra due to statistical and systematic uncertainties. Also shown is the flux of atmospheric neutrinos at the same zenith angle as the source (dashed line), taking into account the source size and angular resolution.

2. Neutrinos from Gamma-ray sources

Determining the flux of neutrinos from measurements of a pionic gamma-ray spectrum is straightforward, as both are the decay products of pions produced in proton-proton collisions. Here we calculate the neutrino spectra using the method of Ref. (Kappes et al., 2007). It is illustrated in Fig. 1, comparing the gamma-ray spectrum from H.E.S.S./MGRO J1908+06 to the calculated neutrino flux at Earth. As the Milagro data extend to $\sim$ 100 TeV without seeing a cut-off, we take the gamma-ray cut-off at 300 TeV, corresponding to a proton cut-off at energies of the order of the 'knee'. The calculated neutrino spectra from all six Milagro hotspots considered here are shown in Fig. 2, assuming an E^{-2} spectrum normalized to the Milagro measurement and also assuming a 300 TeV gamma-ray cut-off.

Neutrino telescopes detect the Cherenkov radiation from secondary particles produced in the interactions of high energy neutrinos in highly transparent and well shielded deep water or ice. They take advantage of the large cross section of high-energy neutrinos and the long range of the muons produced. The detector consists of a lattice of photomultipliers deployed in a shielded and optically clear medium that is transformed into a Cherenkov detector. The IceCube telescope (IceCube Coll. et al., 2006) is under construction and will start taking data with a partial array of 2400 ten inch photomultipliers positioned between 1500 and 2500 meter and deployed as beads on 40 strings below the geographic South Pole. With the completion of the detector by 2010–2011 the instrumented volume will be doubled from 0.5 to 1 km^3.

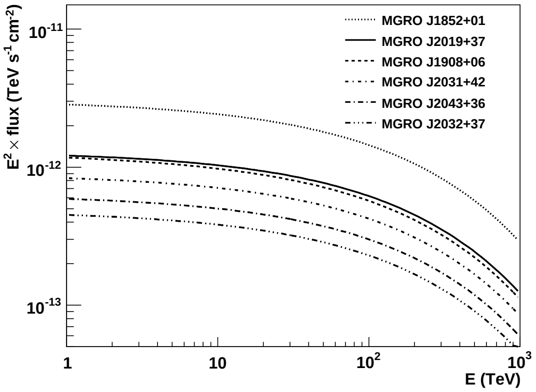

Fig. 2. The calculated neutrino fluxes from six Milagro hotspots, assuming an E^{-2} flux and gamma-ray cut-off at 300 TeV.

The event rate in a detector above a threshold energy $E_{\rm thresh}$ from a neutrino flux dN_ν/dE is given by

$$N_{\rm events} = T \int\limits_{E_{\rm thresh}} A_{\rm eff}(E_\nu)\,\frac{dN_\nu}{dE}\,(E_\nu)\,dE_\nu,$$

where the energy-dependent muon-neutrino effective area $A_{\rm eff}(E_\nu)$ is taken from Ref. (IceCube Coll. et al., 2007). Angular and energy resolution are simulated with values of 0.6° and ± 0.3 in $\log(E_\nu)$, respectively (IceCube Coll. et al., 2004). The flux of atmospheric neutrinos from the interactions of cosmic-ray protons in the Earth's atmosphere, an irreducible background, is tabulated in Ref. (Volkova, 1980) and gives a good parameterization of the AMANDA measurements. Also, we assume no significant contribution from the decay of charmed particles. We take the size of the sources to be the diameter that gives $\sim$ 70% of the measured gamma-ray flux assuming Gaussianity.

We show in Fig. 3 the mean number of neutrino signal events in IceCube in 5 years from MGRO J1908+06 as a function of energy threshold together with the total number of observed events. Given a mean number of signal and background events, we take the number of observed events to be the smallest number of events such that the cumulative Poisson probability for seeing that number of events or more is 50%. Here, the 30% signal reduction due to the finite search bin size is take into account.

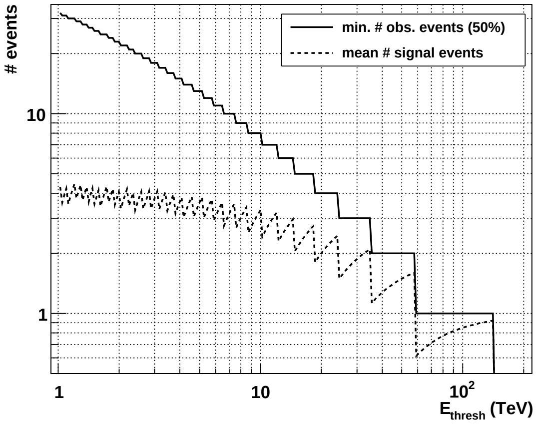

Fig. 3. Mean number of neutrinos from MGRO J1908+06 (dashed line) compared to the minimum total number of events from the search bin (solid line, including background) that will be observed in 50% of cases in 5 years.

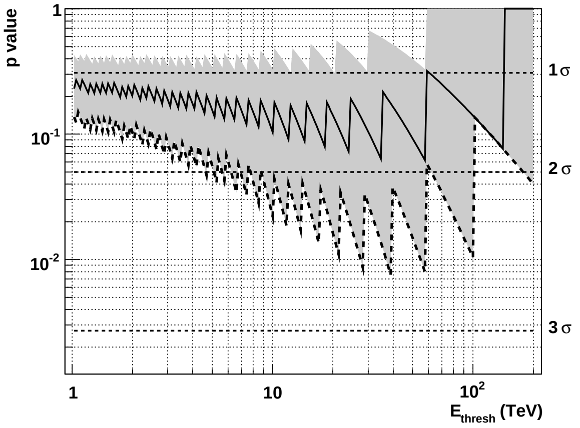

Fig. 4. Poisson probability of excess as a function of threshold energy from MGRO J1908+06 after 5 years. The shaded area represents the uncertainty in the γ-ray measurements. The Milagro data points suggest the lower limit (dashed line).

Given a mean number of background events and a total number of observed events, we can calculate the probability that the observed number of events is due to random fluctuations in the background and hence the statistical significance of the excess. Figure 4 shows the probability of obtaining the calculated total number of observed events assuming the null hypothesis of only background and no signal. Due to the Milagro data points lying in the upper error range of the fitted gamma spectrum (Fig. 1), the Milagro measurements favor the lower-probability range. The structure in the curves is due to integerizing the observed number of events as described above which imposes discontinuous jumps on the

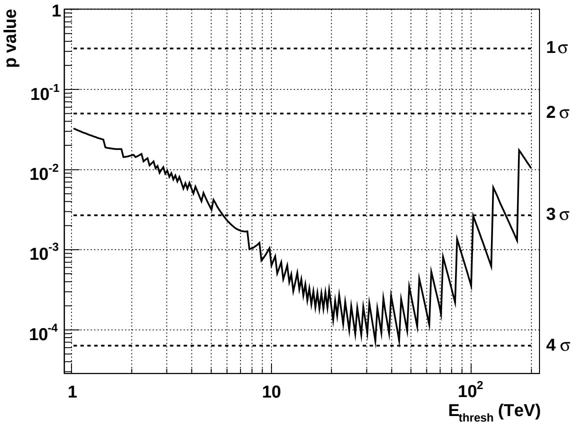

Fig. 5. Poisson probability of observed excess from the Milagro hotspots considered together after 5 years assuming a E^{-2} energy spectrum and a gamma-ray cut-off at 300 TeV.

probability curve.

As the significance of the excess will likely be low even after 5 years, it may well be necessary for a stacked search that will look for correlations between all six Milagro sources of interest simultaneously and the IceCube sky map. The Poisson probability of correlating this catalog with the IceCube sky map after 5 years' time by considering the events and background from all six sources at once is given by Fig. 5.

The figures make clear that the best prospect for detecting these sources is to focus on events above several tens of TeV, where the atmospheric background is very low but there are still sufficient signal events left. Then, a detection of these sources after several years is possible. The use of search methods such as unbinned searches beyond the simple binned method considered here will further increase IceCube's sensitivity.

Although the location of MGRO J1852+01 puts it with a visibility of 50% in the field of view of a future km^3-scale Mediterranean neutrino telescope, there have been no Pevatron candidates discovered in the southern hemisphere, perhaps due to the type of instruments currently operational in that hemisphere. While a high-resolution pointed telescope could resolve what previously appeared to be a diffuse source into its individual parts (supernova remnants and molecular clouds), it is possible that the high density of ambient matter in star-forming regions means that none of the individual parts are alone of sufficient intensity relative to the off-source flux to give sufficient statistical significance. In this case a Milagro-like telescope with a broader field of view such that background measurements are truly 'off-source' would be needed. In this context it is interesting to note that IceCube may be able to detect gamma-rays from the southern sky and therefore be used to search for southern Pevatrons over a broad range similar to Milagro's.

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