Prospects for identifying the sources of the Galactic cosmic rays with IceCube

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(Received 3 March 2008; revised manuscript received 16 July 2008; published 4 September 2008)

We quantitatively address whether IceCube, a kilometer-scale neutrino detector under construction at the South Pole, can observe neutrinos pointing back at the accelerators of the Galactic cosmic rays. The photon flux from candidate sources identified by the Milagro detector in a survey of the TeV sky is consistent with the flux expected from a typical cosmic-ray generating supernova remnant interacting with the interstellar medium. We show here that IceCube can provide incontrovertible evidence of cosmic-ray acceleration in these sources by detecting neutrinos. We find that the signal is optimally identified by specializing to events with energies above 30 TeV where the atmospheric neutrino background is low. We conclude that evidence for a correlation between the Milagro and IceCube sky maps should be conclusive after several years.

DOI: 10.1103/PhysRevD.78.063004 PACS numbers: 95.55.Vj, 95.85.Pw, 95.85.Ry, 98.70.Sa

I. 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 [1]. The cosmic rays will interact with atoms in the interstellar medium to produce pions that decay into photons and neutrinos. Dense molecular clouds, often found in star-forming regions where the supernovae explode, are particularly efficient at converting protons into pions that decay into "pionic" gamma rays and neutrinos. These provide us with indirect but additional evidence for cosmic-ray acceleration and, 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" tells us that there must exist Galactic cosmic-ray sources producing protons with energies of several PeV. These "Pevatrons" will produce pionic gamma rays whose spectrum extends to several hundred TeV without cutoff in interactions with the interstellar medium, in particular, with dense molecular clouds. By straightforward energetics arguments such sources must emerge in global sky surveys with the sensitivity of the Milagro experiment [2]. We will argue that one Pevatron, MGRO J1908 + 06, has likely been identified among five candidates in the current sky map.

Supernovae associated with molecular clouds are a common feature of associations of thousands of OB stars that exist throughout the Galactic plane. Some of the first resolved images of sources in TeV gamma rays were of the supernova remnants RX J1713.7-3946 [3,4] and HESS J1745-290 which illuminate nearby molecular clouds to produce a signal of TeV gamma rays [5]. Although not visible to H.E.S.S., possible evidence has been accumulating for the production of cosmic rays in the Cygnus region of the Galactic plane from a variety of experiments [2,6–9]. Most intriguing is a Milagro report of an excess of events from the Cygnus region at the 10.9σ level [2]. The observed flux within a $3° \times 3°$ window is 70% of the Crab at the median detected energy of 12 TeV and is centered on a source previously sighted by HEGRA. 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. In fact, they report a hotspot, christened MGRO J2019 + 37 [2]. A fit to a circular two-dimensional Gaussian yields a width of $\sigma = (0.32 \pm 0.12)°$, which for a distance of 1.7 kpc suggests a source radius of about 9 pc. As the brightest hotspot in the Milagro map of the Cygnus region, it represents a flux of 0.5 Crab above 12.5 TeV.

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 of $\geq 4.9\sigma$ [10] (the only other Milagro source of such statistical significance being the Crab nebula). 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 con-

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firmed it will be the strongest source in Milagro's entire sky map with a flux about 2.5 times higher than MGRO J2019 + 37 [11]. In the analysis that follows, we will consider the five identified Milagro hotspots as our candidate cosmic-ray accelerators and evaluate the impact of MGRO J1852 + 01 in the event that it is later confirmed as a source.

We focus, in particular, on MGRO J1908 + 06. The H.E.S.S. observations of this source reveal a spectrum consistent with an E^{-2} dependence from 400 GeV to 40 TeV without evidence for a cutoff [12]. In a follow-up analysis [13] 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 [14]. 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 the 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 MGRO J2019 + 37 [15]. 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 [16]. Indeed, there could be many potential accelerators in the Cygnus region, one of the principal star-forming areas of the Galaxy.

In conclusion, evidence tracing the production of these or any other sources of TeV gamma rays to pions produced by cosmic-ray accelerators has been elusive. It is one of the main missions of neutrino telescopes to produce incontrovertible evidence for cosmic-ray production by detecting neutrinos associated with the sources. Particle physics is sufficient to compute the neutrino fluxes associated with the sources discussed. We evaluate in detail the sensitivity of IceCube, the first kilometer-scale neutrino observatory now half complete, to the Milagro sources assuming that they represent the imprint of the Galactic cosmic-ray accelerators on the TeV sky. Here, we include for the first time in these kind of calculations the effect of a finite energy resolution of the detector and a zenith-angle-dependent angular resolution. While the number of events with energies of tens of TeV is relatively low, we establish that this is optimally the energy region where the atmospheric neutrino background is suppressed and an excess from these sources can be statistically established. While observing individual sources may in some cases be challenging, we conclude that evidence for a correlation between the Milagro and IceCube sky maps should be conclusive after several years.

It is important to emphasize that the photon flux from the Milagro sources is consistent with the flux expected from a typical cosmic-ray generating supernova remnant interacting with the interstellar medium (see for instance [1]). In other words, the TeV flux is consistent with the energetics that are required to power the cosmic-ray flux in the Galaxy. Alternative candidates such as micro-quasars have been suggested for the sources of the Galactic cosmic rays. If that were the case, cosmic-ray energetics would require that they leave their imprint on the Milagro sky map, but none have so far been observed.

II. 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 [17]. 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 ~100 TeV without seeing a cutoff, we take the gamma-ray cutoff at 300 TeV, corresponding to a proton cutoff at energies of the order of the knee. The calculated neutrino spectra from the five 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 cutoff.

Earlier work on neutrino event rates from Milagro sources [18] modeled the proton spectrum in supernova

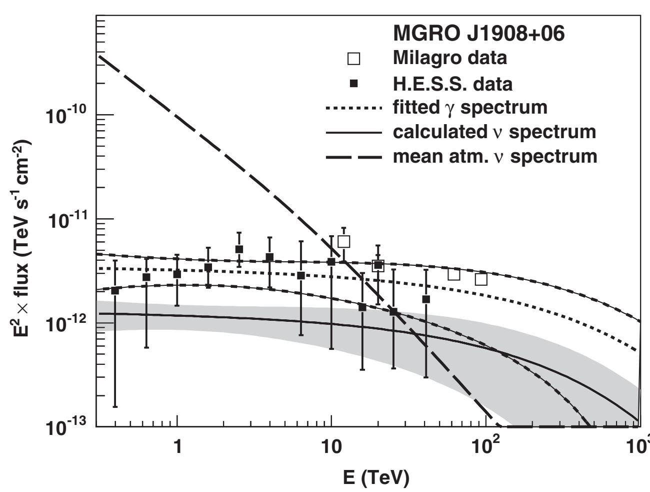

FIG. 1. The γ-ray and neutrino fluxes from MGRO J1908 + 06. The hollow/shaded regions surrounding the fluxes represent the range in the spectra due to statistical and systematic uncertainties. Also shown is the flux of atmospheric neutrinos at the same zenith angle as the source (dashed line), taking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

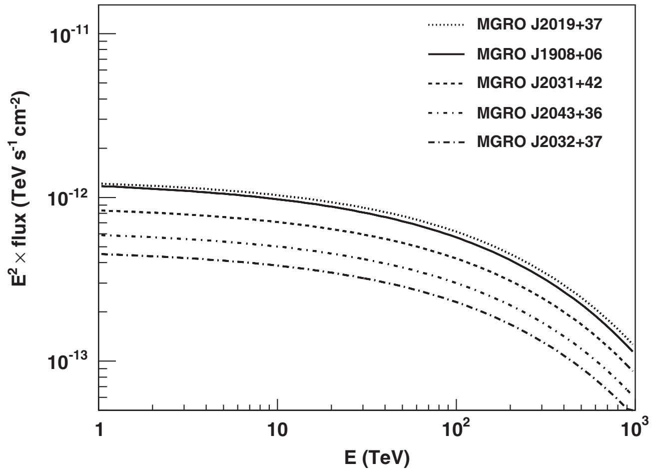

FIG. 2. Calculated neutrino fluxes from five Milagro hotspots, assuming an E^{-2} flux and gamma-ray cutoff at 300 TeV.

remnants and investigated its effect on gamma-ray and neutrino fluxes produced *inside* the accelerators. Given the evidence discussed in the previous section, we assume in this work that the observed gamma rays are not produced directly in the sources but in nearby molecular clouds resulting in harder spectra which extend up to several 100 TeV.

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 with an array of photomultipliers. They take advantage of the large cross section of high-energy neutrinos and the long range of the muons produced. The IceCube telescope [19] is under construction and will start taking data with a partial array of 2400 ten-inch photomultipliers positioned between 1500 and 2500 m 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.

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

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

where the energy-dependent muon-neutrino effective area $A_{\mathrm{eff}}(E_\nu)$ is taken from [20]. The angular resolution is simulated as a function of the zenith angle according to [21] and lies between 0.7° and 0.8° for the Milagro sources. The energy resolution is assumed to be ± 0.3 in $\log(E_\nu)$ which seems achievable given the superior performance of IceCube compared to AMANDA (~ 0.6 in $\log(E_\nu)$ taking [22] and accounting for the kinematics at the neutrino-muon vertex and the energy losses of the muon on its way to the detector). The flux of atmospheric neutrinos from the interactions of cosmic-ray protons in the Earth's atmosphere, an irreducible background, is tabulated in [23] 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 search bin to be the radius that gives ~70% of the measured gamma-ray flux assuming Gaussianity of the source emission and the angular resolution. Table I lists the search bin radii. Given a mean number of background events and a total number of observed events (obtained using Poisson statistics for the sum of signal and background taking into account 30% signal reduction), we calculate the probability (p value) that the observed number of events is due to random fluctuations in the background. We define the significance as the p value for which 50% of experiments yield an equal or lower p value.

TABLE I. Angular radius of the IceCube search bin for each Milagro source.

source	r_{bin} (°)	source	r_{bin} (°)
MGRO J2019 + 37	1.4	MGRO J2043 + 36	1.5
MGRO J1908 + 06	1.1	MGRO J2032 + 37	1.5
MGRO J2031 + 41	1.6	(MGRO J1852 + 01	1.3)

Figure 3 shows the significance as a function of threshold energy for MGRO J1908 + 06 after 10 years' data taking. Because of the Milagro data points lying in the upper error range of the fitted gamma spectrum (Fig. 1), the Milagro measurements favor the higher-significance range. As the significance of the excess will likely be low even after 10 years, it may be necessary to use a stacked search that will look for correlations between all five Milagro sources of interest and the IceCube sky map simultaneously.

Figure 4(a) shows the mean number of signal events in IceCube in 10 years from the five Milagro sources (ex-

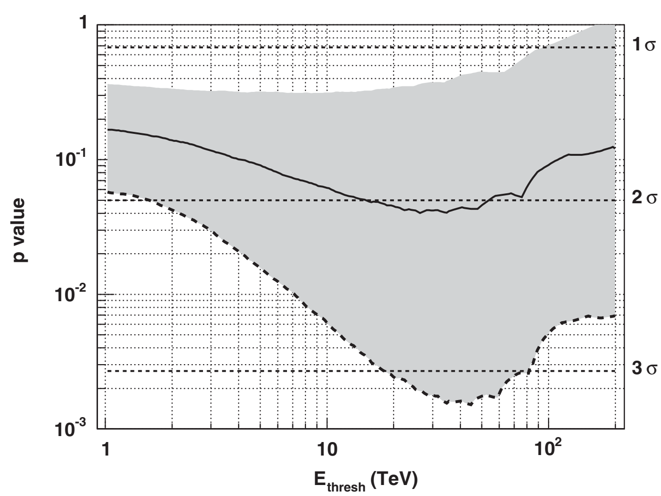

FIG. 3. Significance of excess above background as a function of threshold energy from H.E.S.S./MGRO J1908 + 06 after 10 years. The shaded area represents the uncertainty in the H.E.S.S. γ-ray measurements. The Milagro data points suggest the lower limit (dashed line).

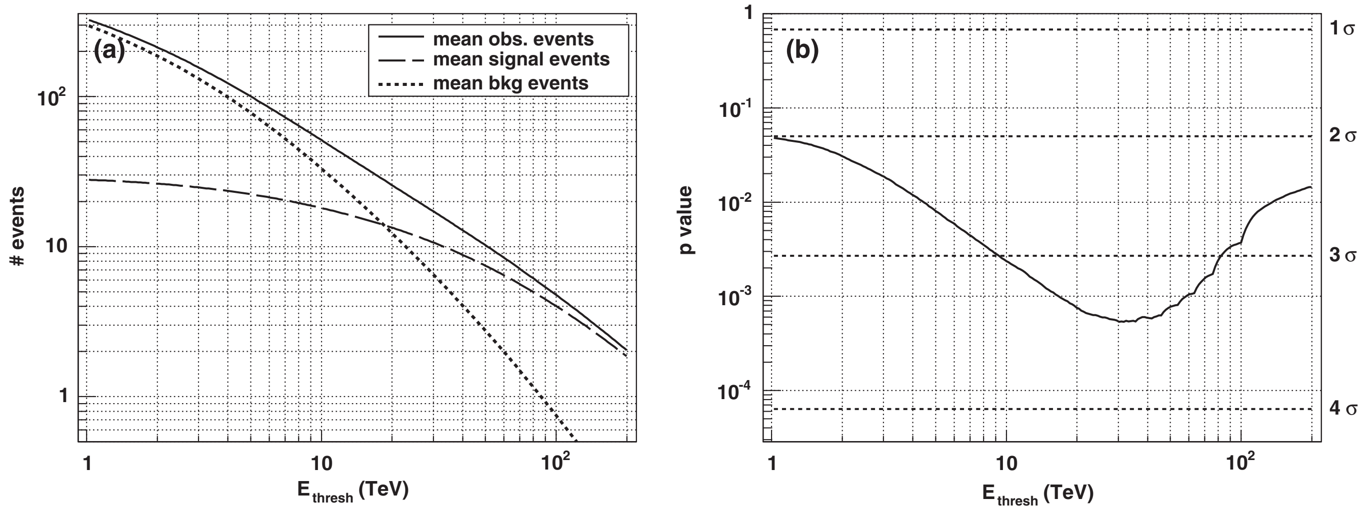

FIG. 4. (a) Mean number of neutrinos from the Milagro hotspots as a function of energy threshold (dashed line) compared to the background (dotted line) and total mean (solid line) number of events from the search bins in 10 years. (b) Corresponding significance of observed excess from the Milagro hotspots.

cluding MGRO 1852 + 01) as a function of energy threshold together with the mean total number of events. The significance of the correlation of this catalog with the IceCube sky map after 10 years' time is given by Fig. 4 (b). If the potential hotspot MGRO J1852 + 01 turns out to be real the same significance would be reached after only 5 years' observation time (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 results we obtain are conservative in several ways. The quoted angular resolution is based on simulations assuming AMANDA technology and reconstruction methods. A not unrealistic increase in the resolution from 0.7°–0.8° to 0.5° improves the significance in Fig. 4(b) to 4σ. Also, the assumed photon fluxes at the sources might be higher due to absorption in the Galactic photon background (especially in the Cygnus region), or, in the case of MGRO J1908 + 06, due to currently ambiguous measurements (see Fig. 1). An overall flux increase by 20% (50%) boosts the significance in Fig. 4(b) to 4σ (5σ). Even reducing the energy resolution to ± 0.5 in $\log(E_\nu)$ still results in a significance of better than 3σ. Furthermore, the use of methods such as unbinned searches beyond the simple binned method considered here will increase IceCube's sensitivity [24].

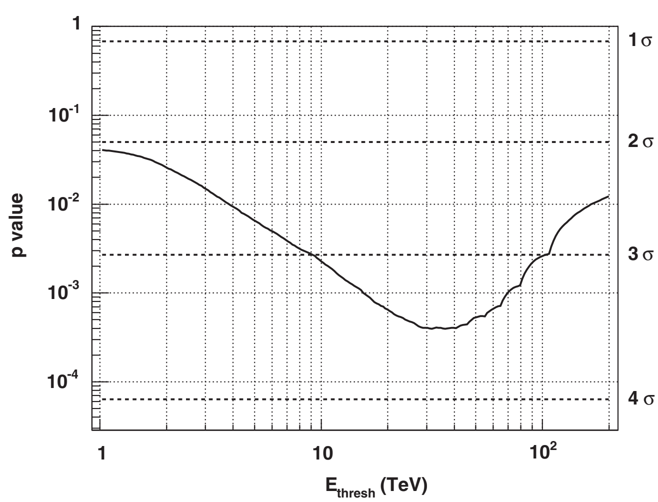

FIG. 5. Significance of observed excess from the Milagro hotspots including the potential hotspot MGRO J1852 + 01 after 5 years of observation time.

III. CONCLUSIONS

Apart from the Crab nebula, Milagro has clearly identified three sources of high-energy gamma-ray emission in their skymap. Two of these sources (MGRO J2019 + 37 and MGRO J2031 + 41) are located in the Cygnus region and one (MGRO J1908 + 06) closer to the Galactic center. Furthermore, the Cygnus region contains two candidate hotspots (MGRO J2043 + 36 and MGRO J2032 + 37). Another potential hotspot (MGRO J1852 + 01) falls currently below the significance threshold set by the Milagro Collaboration. Combining these measurements with measurements from Cherenkov telescopes shows that several of these sources have unusual hard spectra consistent with E^{-2}, where in one case the spectrum seems to extend up to 100 TeV without indication of a cutoff.

Sources producing such hard spectra extending up to 100 TeV and more are required to explain the existence of the knee in the cosmic-ray spectrum around 3 PeV, with young supernova remnants being the best candidates. However, their observation is difficult as these high-energy photons are produced inside the accelerator only within the first few hundred years. Indeed, all current flux calculations for the Milagro sources assume a gamma-ray production scenario inside the acceleration region and in most scenarios predict photon spectra with cutoffs below 100 TeV.

In our paper we adopt the novel idea that a cosmic-ray source can produce a hard gamma-ray spectrum up to high energies over a much longer time of several thousand years if the gamma rays are produced *outside* the acceleration region in the interaction of the source's Pevatron beam with a nearby molecular cloud [16]. Assuming an E^{-2} spectrum with a cutoff at 300 TeV (consistent with a proton cutoff at the knee) we demonstrate that IceCube will be able to see these sources after several years of observation. For the significance calculations we use results from a detailed detector simulation and take into account the energy resolution and zenith-angle-dependent angular resolution. The former is especially important as we demonstrate that the highest sensitivity is obtained by specializing to events with energies above 30 TeV. Similar studies have so far neglected energy migration effects.

With a visibility of 50%, the location of MGRO J1908 + 06 puts it within reach of a future km^3-scale Mediterranean neutrino telescope. However, in the southern hemisphere no Pevatron candidates have been discovered so far, perhaps because no all-sky instrument like Milagro is 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 prevents individual sources from dominating the off-source flux to give sufficient statistical significance for a pointing telescope. 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 [25] and therefore be used to search for southern Pevatrons over a broad range similar to Milagro's.

ACKNOWLEDGMENTS

This research was supported in part by the National Science Foundation under Grant No. OPP-0236449, in part by the U.S. Department of Energy under Grant No. DE-FG02-95ER40896, and in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation. A. K. acknowledges support by the EU Marie Curie OIF program.

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