Gamma ray astronomy with muons

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Abstract

Although gamma ray showers are muon-poor, they still produce a number of muons sufficient to make the sources observed by GeV and TeV telescopes observable also in muons. For sources with hard gamma ray spectra there is a relative ‘enhancement’ of muons from gamma ray primaries as compared to that from nucleon primaries. All shower gamma rays above the photo-production threshold contribute to the number of muons $N_\mu$, which is thus proportional to the primary gamma ray energy. With gamma ray energy 50 times higher than the muon energy and a probability of muon production by the gammas of about 1\%, muon detectors can match the detection efficiency of a GeV satellite detector if their effective area is larger by $10^4$. The muons must have enough energy for sufficiently accurate reconstruction of their direction for doing astronomy. These conditions are satisfied by relatively shallow neutrino detectors such as AMANDA and Lake Baikal and by gamma ray detectors like MILAGRO. TeV muons from gamma ray primaries, on the other hand, are rare because they are only produced by higher energy gamma rays whose flux is suppressed by the decreasing flux at the source and by absorption on interstellar light. We show that there is a window of opportunity for muon astronomy with the AMANDA, Lake Baikal and MILAGRO detectors.

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I. INTRODUCTION

Instruments exploiting the air Cherenkov technique have extended the exciting astronomy revealed by the Compton G(amma) R(ay) O(bservatory) into the TeV energy range [1]. The photon spectra of the Crab nebula, the pulsar PSR 1706-44 and of the active galaxy Markarian 421, observed by satellite experiments at GeV energies, are known to extend to higher energy, e.g. well above 10 TeV for the Crab. More interestingly, the galaxy Markarian 501, recently detected in the TeV range, is not a confirmed GeV gamma ray source.

High energy gamma rays produce muons in the Earth’s atmosphere that can be detected and reconstructed in relatively shallow underground neutrino detectors such as the AMANDA and Lake Baikal, which are positioned at a modest depth of order 1 kilometer [2] or in a surface detector like MILAGRO. The neutrino detectors are sensitive to muon energies of a few hundreds of GeV and the Milagro telescope detects muons above 1.5 GeV, well below the TeV thresholds of deep underground detectors. Although muons from such sources compete with a large background of down-going cosmic ray muons, they can be identified provided the detectors have a sufficient effective area. Unlike air Cherenkov telescopes, muon detectors cover a large fraction of the sky with a large duty cycle, e.g. 100% efficiency for more than a quarter of the sky in the case of the AMANDA detector with a South Pole location. The advantage is considerable in studying the emission from highly variable sources. Useful results may, possibly, be obtained with the partially deployed instruments, even before they achieve the necessary up-down discrimination to identify neutrinos. Moreover, background multi-muon bundles, which are difficult to reconstruct, can be conveniently rejected without suppression of the predominantly single-muon gamma ray signal.

In this paper we demonstrate how these muon energy ranges provide a window of opportunity for muon astronomy. The muons are sufficiently energetic to leave tracks that can be adequately measured by the Cherenkov technique. The direction of the parent photon can be inferred with degree accuracy in the case of AMANDA and Lake Baikal and a few degree accuracy in the case of MILAGRO.

Detected muons originate in gamma showers with some 50 times higher energies. Such gamma rays have been detected, at least from two galactic and two extra-galactic sources, by air-Cherenkov telescopes. A multi-TeV air shower will produce a 100 GeV muon with
a probability of order 1% \(3\), sufficient to observe the brightest sources using relatively modest-size detectors with effective area of order 1000 m\(^2\) or more. The probability that such photons produce TeV-energy muons which trigger the deep underground detectors, such as those in the Gran Sasso tunnel, is small. TeV muons are produced by photons of several tens of TeV energy and above. Their rates are suppressed and, more importantly, it is not clear whether the source spectra extend far beyond the TeV region. They most likely do not. In the case of galactic sources, such as the Crab supernova remnant, the current thinking is that the high energy photons are produced by inverse Compton scattering of electrons accelerated by the pulsar \(4\). Such a purely electromagnetic accelerator is unlikely to produce photons far beyond the observed spectrum which extends to 10 TeV. While the vast majority of GeV gamma ray sources display a \(E^{-(\gamma+1)}\) energy spectrum with \(\gamma \approx 1\) \(7\), the steepening slope of the Crab spectrum may provide us with a glimpse of a steep cutoff not far beyond the reach of the data; see Table 1. Another type of GeV \(5\), and possibly TeV, galactic gamma ray sources are the supernova remnants, presumably the acceleration sites of the galactic cosmic rays. The recent observation of hard X–rays at SN1006 \(8\) is consistent with the acceleration of electrons to 100 TeV. Extragalactic sources such as the active galaxy Markarian 421 may, on the other hand, be true high energy accelerators producing protons with sufficient energy to account for the high energy cosmic ray spectrum which extends beyond \(10^{20}\) eV. Even in this case, the existence of higher energy photons is not guaranteed because they may be absorbed in the source, or on the interstellar infrared and microwave background \(8,9\). Nearby active galactic nuclei in the local cluster or the super-galactic plane, with redshift less than 0.03 or so, represent promising sources in this respect. Examples are listed in Table 1 where, as usual, we have parameterized the gamma ray flux as

\[
\frac{dN_\gamma}{dE_\gamma} = \frac{F_\gamma}{E^{(\gamma+1)}} 10^{-12} \text{cm}^{-2} \text{s}^{-1}.
\]

Throughout this paper energies are in TeV units. The high energy luminosity of the source is described by the parameter \(F_\gamma\) which in the EGRET catalog \(7\) denotes the flux of photons above 100 MeV in units of \(10^{-8}\) photons per cm\(^2\) per second. For flat \((\gamma = 1)\) spectra the same number will apply to the flux of TeV gamma rays in units \(10^{-12}\). Most EGRET sources with measured energy spectrum have \(\gamma \leq 1\). For the Crab supernova however
the TeV flux is reduced by one order of magnitude with $F_{\gamma} = 20$ in the TeV region \[10\]. This number is bracketed by the 7(50) Markarian 421 flux in its low (high) state \[11\]. So, interestingly, galactic and nearby extra-galactic sources produce comparable photon fluxes at Earth despite the $10^5$ ratio of their distances. Sources such as the Vela pulsar, the galactic center and the cluster of four unidentified gamma ray sources in the direction of the spiral arm near Cygnus, may be TeV gamma ray emitters brighter by more than one order of magnitude. We refer to Table 1 for a partial list.

II. MUON RATES FROM GAMMA RAY SOURCES

Gamma rays initiate atmospheric cascades of mostly electrons and photons, but also some muons. Muons originate from the decay of pions which are photoproduced by the shower photons. The number of muons with energy above $E_{\mu}$ in a shower initiated by a photon of energy $E_{\gamma}$ was computed some time ago. For $E_{\mu}$ in the range from 0.1 to 1 TeV the number of muons in a photon shower can be parameterized as

$$N_{\mu}(E_{\gamma} > E_{\mu}) \approx \frac{2.14 \times 10^{-5}}{\cos \theta} \frac{1}{(E_{\mu}/\cos \theta)} \frac{E_{\gamma}}{(E_{\mu}/\cos \theta)} \left[ \frac{E_{\gamma}}{(E_{\mu}/\cos \theta)} \right] .$$

Energy units are TeV and the parameterization is adequate for $E_{\gamma}/E_{\mu} \geq 10$. The estimate is conservative and below the rate of muons obtained by Bhattacharyya \[12\], who updated the calculations of reference \[3\] taking into account the latest measurements of the high energy photoproduction cross section at HERA. TeV-muons are also produced by muon pair production and the decay of charm particles. For the lower energy muons considered here these additional sources can be neglected \[3\]. For muons of energy lower than 0.1 TeV, more complete formulas of \[3\] must be used and probability of muon decay incorporated.

The muon flux produced by a gamma ray source is obtained by convolution of Eqs. 1 and 2:

$$N_{\mu}(>E_{\mu}) = \int_{E_{\gamma \min}}^{E_{\gamma \max}} dE_{\gamma} \frac{F_{\gamma} 10^{-12}}{E_{\gamma}^{\gamma+1}} \frac{2.14 \times 10^{-5}}{E_{\mu}} \left( \frac{E_{\gamma}}{E_{\mu}} \right)$$

$$\approx 2 \times 10^{-17} \frac{F_{\gamma}}{\cos \theta (E_{\mu}/\cos \theta)^{\gamma+1}} \ln \left( \frac{E_{\gamma \max}}{E_{\gamma \min}} \right) .$$

Here $E_{\mu}$ is the vertical threshold energy of the detector, e.g. 0.18 TeV for the AMANDA detector. $\theta$ is the zenith angle at which the source is observed. It is, conveniently, time-independent for the AMANDA detector with a South Pole location. Photons with energy...
ranging from a minimum energy $E_{\gamma\text{min}} \simeq 10 \times E_\mu / \cos \theta$ to the maximum energy of the source $E_{\gamma\text{max}}$ contribute to the production of the observed muons. The highest energy photons dominate. For this reason the muon flux depends critically on the high energy flux of the source. The factor $f$ is a correction factor which can be parametrized as

$$f = \left( \frac{E_\mu / \cos \theta}{0.04} \right)^{0.53}.$$

(5)

The flux of muons varies with the vertical threshold of the detector as $E_{\mu}^{-(\gamma+1)}$. This behavior is only approximate and assumes that the integrand in Eq. 3 spans many decades of the $E_{\gamma}^{-2}$ spectrum between $E_{\gamma\text{min}}$ and $E_{\gamma\text{max}}$. Otherwise, the dependence is moderated, an effect which is described by the factor $f$. In the end our parameterization reproduces the explicit Monte Carlo results [3].

A corresponding calculation has to be carried out to determine the background of muons from primary cosmic rays. For the AMANDA detector the gamma ray signal has to be extracted from a background of cosmic ray muons which is empirically $3.3 \times 10^{-6}$ muons per cm$^2$ per second per steradian and falls with zenith angle as $\cos \theta^{2.8}$ at a detector depth of 1 kilometer water-equivalent [13]. For the MILAGRO detector the cosmic ray muon flux has a $\cos(\theta)^2$ angular distribution and the rate is $\sim 0.01$ muons in the same units [14].

For AMANDA the relevant number is the background muons in a pixel of $\delta \times \delta$ degrees which is given by

$$N_{\mu}^{\text{back}}(\text{m}^{-2}\text{yr}^{-1}) \simeq 325 \cos \theta^{2.8} \delta^2.$$

(6)

As previously mentioned the background includes some fraction of multi-muon events. Rejecting multi-muon events not only improves signal-to-noise, it should improve angular resolution which is often degraded by the poor reconstruction of complex muon bundles initiated by high energy cosmic ray muons. For MILAGRO, which detects low energy muons the mean angular accuracy achievable is dominated by the spreading due to transverse momentum kick given to the pions at production and is of the order of $3^\circ$. The effective area of MILAGRO detector for muons is $1.5 \times 10^3$ m$^2$.

III. SUMMARY OF RESULTS AND EXAMPLES
A. The AMANDA Telescope:

Our results can be conveniently summarized as follows. The number of events per year in a detector of effective area $A$ m$^2$ and vertical threshold of 0.18 TeV is given by

$$N_\mu(\text{yr}^{-1}) = 6.7 \times 10^{-6} \frac{F_\gamma}{\cos \theta} \frac{1}{(E_\mu/\cos \theta)^{\gamma+1}} \ln\left(\frac{\cos \theta E_{\gamma \text{max}}}{10 E_\mu}\right) fA.$$  \hspace{1cm} (7)

We recall that all energies are in TeV units. The signal-to-noise, defined as the number of events divided by the square root of the number of background events in a pixel of $\delta \times \delta$ degrees, depends on detector area and zenith angle as

$$S/\sqrt{N} \sim \frac{\sqrt{A}}{\cos \theta^{0.9} \delta}.$$ \hspace{1cm} (8)

The formula simply expresses that signal-to-noise is improved for increased area, better resolution and for sources observed at large zenith angle where the cosmic ray background muon rate is reduced.

To demonstrate the power of a relatively shallow neutrino detector as a gamma-ray telescope we start with an optimistic, though not unrealistic example. We take the Vela pulsar with $F_\gamma = 932$ and $\theta = 45^\circ$ at the South Pole. This assumes that the source flux is not cut off at high energy and the spectral index $\gamma$ is 1. We will however assume that $E_{\gamma \text{max}}$ is only 10 TeV (the muon flux is increased by a factor 4.4 if the spectrum extends to 1000 TeV). For a nominal detector with effective area $10^4$ m$^2$ area and $\delta = 1^\circ$ angular resolution we obtain 5000 events per year above $E_\mu = \frac{180 \text{GeV}}{\cos(45^\circ)} = 255$ GeV on a background of $1.2 \times 10^6$ or an $S/\sqrt{N}$ ratio in excess of 4.

For the blazar Markarian 421 the TeV-flux, averaged between the high and low state, corresponds to $F_\gamma \approx 35$. Our nominal detector should collect 442 events from such a source at a zenith angle of 60$^\circ$ per year assuming $E_{\gamma \text{max}} = (100 \text{ TeV})$. This would give a $S/\sqrt{N}$ ratio of 0.6.

As a final example we propose the 4 sources in a 5$^\circ$ by 3$^\circ$ declination/right ascension bin in the direction of the spiral arm in Cygnus. For this cluster of sources $F_\gamma = 335$ and $\theta = 60^\circ$; we will assume that $E_{\gamma \text{max}} = 100$ TeV. A $10^4$ m$^2$ detector will collect 3700 events on a background of 18 million in the bin containing the sources for $S/\sqrt{N}$ close to 1. No precise reconstruction is required. A similar argument should apply to the galactic plane.
B. The MILAGRO Telescope

As the muon threshold of MILAGRO is only 1.5 GeV, it can probe lower energy gamma rays than that for the neutrino telescopes. It has sensitivity to an energy range which overlaps that of Whipple telescope. The signal that can be observed depends sensitively on the cutoff of the gamma ray spectrum in the 100 GeV to 10 TeV energy range. As mentioned earlier, the $3^\circ$ intrinsic angular resolution requires that one must use a $4.7^\circ$ bin size to collect $\sim 70\%$ of the gamma ray events. The background cosmic ray flux is then $\sim 930$ Hz. The sensitivity of MILAGRO muons for gamma ray searches is shown in Table 2 for several sources, which gives the time in seconds required to obtain a $5.5\sigma$ significance result, for different cutoff energies of the primary gamma spectrum. The first column identifies the source, the second and third define the source parameters. The fourth column gives the maximum energy cutoff that is assumed for the incident gamma ray spectrum, fifth the expected rates for signal, and the last column gives the time in seconds required to obtain a $5.5\sigma$ observation.

Table 2 shows that Geminga may be observed even if the cutoff is only 300 GeV, in about a year. If arrival times of events can be put into the data stream for events coming from Geminga, period analysis could be applied to improve the signal to noise ratio and probably lower the cutoff energy down to 50 GeV.

Halzen 4 is a set of 4 Egret sources, described in the previous subsection, which are within about 2 degrees of each other with a reasonably flat spectra. It is observable, if the spectrum extends to energies above a TeV.

Finally, we note that stronger GRBs should be observable, even with a 1.5 energy spectrum, if they last as long as the times indicated in the last column. For the GRBs with flatter spectra the possibility of observation is enhanced. The dependence on cutoff energy is also indicated in the table. For several cases one can see a signal even if the cutoff is as low as 100 GeV. Thus, at least for GRBs the muon observation allows us to extend the energy range of Milagro to lower cutoff energies.

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TABLE I. A partial list of potential VHE $\gamma$-ray sources based on the 2nd EGRET catalog. Groups of sources that are difficult to resolve are combined. The position for such sources are averaged with the EGRET $\gamma$-ray flux and a solid angle (ster) for the group is given. $F_\gamma$ is the average number of photons above 100 MeV in units of $10^{-8}$ cm$^{-2}$ s$^{-1}$, $\gamma$ is the spectral index. The check marks indicate sources observed by TeV Cherenkov telescopes.

| RA        | Dec   | $F_\gamma$ | $\gamma$ | $\Delta\Omega$ | Source          | VHE? |
|-----------|-------|------------|----------|-----------------|-----------------|------|
| 128.8     | −45.2 | 932±8      | 0.6–0.9  | —               | Vela pulsar      | √    |
| 98.5      | 17.8  | 374±5      | 0.4–0.7  | —               | Geminga pulsar   | √    |
| 306.1     | 39.2  | 335±9      | —        | 3.3 $\times$ 10$^{-3}$ | J2019+3719 |      |
|           |       |            |          |                 | J2020+4026       |      |
|           |       |            |          |                 | J2026+3610       |      |
|           |       |            |          |                 | J2033+4122       |      |
| 266.8     | −29.8 | 218±10     | —        | 2.7 $\times$ 10$^{-4}$ | J1746−2852 |      |
|           |       |            |          |                 | J1747−3039       |      |
| 184.56    | −5.8  | 212±3      | 1.2–1.5  | —               | Crab pulsar      | √    |
| 257.4     | −44.9 | 144±5      | —        | —               | PSR1706−44       | √    |
| 217.7     | −23.4 | 121±9      | —        | 3.6 $\times$ 10$^{-4}$ | J1801−2312 |      |
|           |       |            |          |                 | J1811−2339       |      |
| 213.2     | −62.2 | 103±9      | —        | —               | J1412−6211       |      |
| 155.4     | −58.6 | 99±5       | —        | —               | J1021−5835       |      |
| Source   | $F_γ$     | Diff slope | $E_{max}$ | $S$ (Hz) | Time (sec) |
|----------|-----------|------------|-----------|----------|------------|
|          | $\gamma$ | GeV        |           |          | to 5.5$σ$ |
| Geminga  | 374       | 1.5        | $10^2$    | .013     | 1.7$x10^8$|
| Geminga  | 374       | 1.5        | $3\times10^2$ | .04     | 1.4$x10^7$|
| Geminga  | 374       | 1.5        | $10^3$    | .15      | 1.2$x10^6$|
| Halzen 4 | 336       | 1.7        | $10^4$    | .11      | 2.1$x10^6$|
| Halzen 4 | 336       | 1.7        | $5\times10^3$ | .08     | 4.4$x10^6$|
| Halzen 4 | 336       | 1.7        | $3\times10^3$ | .06     | 7.5$x10^6$|
| Halzen 4 | 336       | 1.7        | $1\times10^3$ | .03     | 2.8$x10^7$|
| AGN      | 100       | 1.7        | $10^4$    | .035     | 2.4$x10^7$|
| GRB      | 6.6e6     | 2.5        | $1\times10^3$ | 16.7    | 102        |
| GRB      | 6.6e6     | 2.5        | $5\times10^2$ | 14.8    | 131        |
| GRB      | 6.6e6     | 2.5        | $3\times10^2$ | 13.0    | 167        |
| GRB      | 6.6e6     | 2.5        | $2\times10^2$ | 8.4     | 404        |
| GRB      | 6.6e6     | 2.3        | $1\times10^3$ | 36.6    | 21         |
| GRB      | 6.6e6     | 2.3        | $5\times10^2$ | 31.3    | 29         |
| GRB      | 6.6e6     | 2.3        | $3\times10^2$ | 27.05   | 39         |
| GRB      | 6.6e6     | 2.3        | $1\times10^2$ | 16.4    | 106        |
| GRB      | 6.6e5     | 2.5        | $1\times10^3$ | 1.67    | 10210      |
| GRB      | 6.6e5     | 2.5        | $5\times10^2$ | 1.47    | 13114      |
| GRB      | 6.6e5     | 2.5        | $3\times10^2$ | 1.30    | 16788      |
| GRB      | 6.6e5     | 2.5        | $1\times10^2$ | .84     | 40455      |
| GRB      | 6.6e5     | 2.3        | $10^3$    | 3.66     | 2125       |
| GRB      | 6.6e5     | 2.3        | $5\times10^2$ | 3.14    | 2899       |
| GRB      | 6.6e5     | 2.3        | $3\times10^2$ | 1.63    | 10597      |
| GRB      | 6.6e4     | 2.5        | $1\times10^3$ | .16     | $10^6$     |
| GRB      | 6.6e4     | 2.0        | $1\times10^3$ | 1.32    | 1.6$x10^4$|