GAMMA RAY ASTRONOMY WITH UNDERGROUND DETECTORS

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ABSTRACT

Underground detectors measure the directions of up-coming muons of neutrino origin. They can also observe down-going muons made by gamma rays in the Earth’s atmosphere. Although gamma ray showers are muon-poor, they produce a sufficient number of muons to detect the sources observed by GeV and TeV telescopes. With a threshold higher by one hundred and a probability of muon production of about 1% for the shallower AMANDA and Lake Baikal detectors, these instruments can, for a typical GRO source, match the detection efficiency of a GeV satellite detector since their effective area is larger by a factor $10^4$. The muons must have enough energy for accurate reconstruction of their direction. Very energetic muons 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 in the 100 GeV energy region which nicely matches the threshold energies of the AMANDA and Lake Baikal detectors.
1 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\textsuperscript{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. all the way to 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.

TeV gamma rays produce muons in the Earth’s atmosphere that can be detected and reconstructed in relatively shallow underground detectors such as the AMANDA and Lake Baikal detectors, which are positioned at a modest depth of order 1 kilometer \textsuperscript{2}. They are therefore sensitive to muon energies of a few hundreds of 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 searched for with relatively large effective area detectors. Unlike air Cherenkov telescopes, muon detectors cover a large fraction of the sky. 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 the 100 GeV muon energy range provides 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. Hundred-GeV muons originate in TeV gamma showers whose existence has been demonstrated, at least for 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\%\textsuperscript{3}, sufficient to observe the brightest sources with 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. The rates are however suppressed and, more importantly, it is not clear whether the 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 $E^{-\gamma}$ energy spectrum with $\gamma \approx 1[5]$, 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. On the contrary, extra-galactic sources such as the active galaxy Markarian 421, may 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. This does not guarantee emission of high energy photons which may be absorbed in the source, or on the interstellar infrared and microwave background\[6\]. Very near active galactic nuclei, in the local cluster or the super-galactic plane and 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 parametrized the gamma ray flux as

$$\frac{dN_\gamma}{dE_\gamma} = \frac{F_\gamma}{E^{(\gamma+1)}} \times 10^{-12} \text{cm}^{-2} \text{s}^{-1}.$$  \hspace{1cm} (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\[5\] 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\[7\]. This number is bracketed by the 7–50 Markarian 421
flux in its low and high states. 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.

Table 1: 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 $10^{-8}\text{cm}^{-2}\text{s}^{-1}$.

| RA    | Dec  | $F_\gamma$ | $\gamma_d$ | $\Delta\Omega$ | Source          | VHE? |
|-------|------|------------|------------|----------------|-----------------|------|
| 128.8 | -45.2| 932 ± 8    | 1.6–1.9    | —              | Vela pulsar     | √    |
| 98.5  | 17.8 | 374 ± 5    | 1.4–1.7    | —              | Geminga pulsar  | √    |
|       |      | 335 ± 9    | —          | $3.3 \times 10^{-3}$|
| 306.1 | 39.2 | 335 ± 9    | —          | —              | J2019+3719      | —    |
|       |      |           |            |                | J2020+4026      | —    |
|       |      |           |            |                | J2026+3610      | —    |
|       |      |           |            |                | J2033+4122      | —    |
| 266.8 | -29.8| 218 ± 10   | —          | $2.7 \times 10^{-4}$|
|       |      | 121 ± 9    | —          | —              | J1746–2852      | —    |
|       |      | 212 ± 3    | 2.2–2.5    | —              | J1747–3039      | —    |
| 184.56| -5.8 | 144 ± 5    | —          | —              | Crab pulsar     | √    |
| 257.4 | -44.9| 144 ± 5    | —          | —              | PSR1706–44      | √    |
| 217.7 | -23.4| 121 ± 9    | —          | $3.6 \times 10^{-4}$|
|       |      | 103 ± 9    | —          | —              | J1801–2312      | —    |
|       |      | 99 ± 5     | —          | —              | J1811–2339      | —    |
| 155.4 | -58.6| 99 ± 5     | —          | —              | J1412–6211      | —    |
|       |      |           |            |                | J1021–5835      | —    |
2 Muon Rates from Gamma Ray Sources

Gamma rays initiate atmospheric cascades of not only electrons and photons, but also muons. Muons originate from the decay of pions which are photoproduced by shower photons. The number of muons with energy above $E_\mu$ in a shower initiated by a photon of energy $E_\gamma$ has been computed some time ago and for $E_\mu$ in the range from 100 to 1000 GeV can be parametrized as

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

(2)

for $E_\gamma/E_\mu \geq 10$. This estimate is conservative and below the rate of muons obtained by Bhattacharyya[9], who updated the calculations of reference[3] taking into account the latest measurements of the high energy photoproduction cross section at HERA. Additional TeV-muons are produced by pair production and the decay of charm particles. For lower energy muons these additional sources can be neglected[3]. The muon flux produced by a gamma ray source is obtained by convolution of Eqs. 1 and 2:

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

(3)

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

(4)

Here $E_\mu$ is the vertical threshold energy of the detector, e.g. 0.18 TeV for the AMANDA detector. Photons with energy ranging from a minimum energy $E_{\gamma_{\min}} \approx 10 \times E_\mu/\cos \theta$ to the maximum energy of the source $E_{\gamma_{\max}}$ mainly contribute to the production of the observed muons. The highest energy photons dominate. For this reason the muon flux critically depends on the high energy flux of the source. $\theta$ is the zenith angle at which the source is observed. This angle is, conveniently, time-independent for the AMANDA detector with a South Pole location. 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 vertical threshold 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 parametrization reproduces the explicit Monte Carlo results\[3\].

Above signal has to be extracted from a background of cosmic ray muons which is empirically $2 \times 10^{-7}$ 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\[10\]. Relevant is the number of background muons in a pixel of $\delta \times \delta$ degrees which is given by

$$N_{\mu}^{\text{back}}(m^{-2} \text{ yr}^{-1}) \simeq 20 \cos \theta^{2.8} \delta^2 . \quad (6)$$

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.

3 Summary of Results and Examples

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

$$N_\mu(\text{yr}^{-1}) = 6.7 \times 10^{-5} \frac{F_\gamma}{\cos \theta} \frac{1}{(E_\mu/ \cos \theta)^{\gamma+1}} \ln\left(\frac{\cos \theta E_{\gamma \text{max}}}{10E_\mu}\right) fA . \quad (7)$$

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

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

The formula simply expresses that signal-to-noise is improved for increased area, better resolution and for sources at large zenith angle in the sky where the cosmic ray background muon rate is reduced.
To demonstrate the power of a neutrino 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. 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 on a background of $7.5 \times 10^4$ or a signal to noise in excess of 10. $S/\sqrt{N}$ exceeds unity for a detector as small as 40m$^2$ collecting 20 events per year. For a detector with a poor $5^\circ$ resolution this area is 200m$^2$. The partially deployed AMANDA and Lake Baikal instruments may already be sensitive to such a source.

For the blazar Markarian 421 the TeV-flux, averaged between the high and low state, corresponds to $F_\gamma \simeq 35$. Our nominal detector should collect $1.8 \times 10^2(8.2 \times 10^2)$ events per year assuming $E_\gamma = 10(100 \text{ TeV})$ for a $S/\sqrt{N}$ of 0.7(2.8). For a blazar known to emit 10 TeV gamma rays the assumption of a cut-off of only 10 TeV is likely to be conservative.

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 $E_\gamma = 100 \text{ TeV}$. A $10^4 \text{ m}^2$ detector will collect 6300 events on a background of 0.5 million in the bin containing the sources for $S/\sqrt{N} = 8.9$. No precise reconstruction is required and the sources should be detected, even if their spectrum cuts off at 10 TeV.

Acknowledgments

This research was supported 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.

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