Constraints on the TeV source population and its contribution to the galactic diffuse TeV emission

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ABSTRACT

The detection by the HESS atmospheric Cerenkov telescope of fourteen new sources from the Galactic plane makes it possible to estimate the contribution of unresolved sources like those detected by HESS to the diffuse Galactic emission measured by the Milagro Collaboration. The number-intensity relation and the luminosity function for the HESS source population are investigated. By evaluating the contribution of such a source population to the diffuse emission we conclude that a significant fraction of the TeV energy emission measured by the Milagro experiment could be due to unresolved sources like HESS sources. Predictions concerning the number of sources which Veritas, Milagro, and HAWC should detect are also given.

Subject headings: gamma rays: theory

1. Introduction

The Galactic diffuse $\gamma$-ray emission is believed to be mostly produced in interactions of cosmic rays with the matter and the radiation fields in the Galaxy, the main production mechanisms being electron non-thermal Bremsstrahlung, Inverse Compton scatterings off the radiation fields and pion decay processes in inelastic collisions of nuclei and matter. Although the standard production mechanisms of $\gamma$-rays (Bertsch et al. 1993) explain generally well the spatial and energy distribution of the emission below 1 GeV, the model does not match EGRET observations of the $\gamma$-ray sky above 1 GeV [Hunter et al. 1997]. Many possible explanations have been proposed to account for the GeV excess [Aharonian & Atoyan 2001; Strong et al. 1999, 2004; Kamae et al. 2006; de Boer et al. 2005; Bergstrom et al.]

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In any case a major difficulty when studying the diffuse emission is to disentangle the truly diffuse emission from that produced by unresolved sources.

The TeV diffuse $\gamma$-ray emission from the Galactic Plane (Atkins et al. 2005) and from the Cygnus region (Abdo et al. 2007) has been measured by Milagro, a water Cerenkov telescope surveying the northern sky at TeV energies (Atkins et al. 2000, 2003). The diffuse emission measured by Milagro is $(7.3 \pm 1.5 \pm 2.3) \times 10^{-11}$ photons cm$^{-2}$ sr$^{-1}$ s$^{-1}$ for $E > 3.5$ TeV in the region $40^\circ < l < 100^\circ$ (Atkins et al. 2005). A measurement of the TeV $\gamma$-ray diffuse flux is important, as it allows us to calculate what fraction of the emission is produced through inverse Compton and what fraction is produced through pion-decay mechanism. Milagro result, which is consistent with EGRET data above 1 GeV, seems to exclude an additional hard spectrum component continuing to above 10 TeV to explain the 60 per cent excess of EGRET flux compared to $\pi_0$-decay production mechanism due to the local cosmic ray flux (Hunter et al. 1997). Recently Prodanovic et al. (2006) have argued that no strong signal of pion decay is seen in the $\gamma$-ray spectrum. The pion decay mechanism would not be able to explain the excess above 1 GeV and the Milagro measurements of the diffuse flux at higher energies reveals a new excess at TeV energies. Prodanovic et al. (2006) investigated several possibilities for what might cause the TeV excess, among them possible dark matter decay, contribution from unresolved EGRET sources or sources that are only bright in the TeV range. An extrapolation of the EGRET sources within the range in Galactic longitude of the Milagro observation overestimates the diffuse TeV flux measured. However, there could be a population of sources undetectable by EGRET, but contributing to both the GeV and TeV excess diffuse emission. Recent observations by the TeV observatory, HESS, in fact point to a new class of hard spectrum TeV sources located close to the Galactic Plane, within $\pm 1$ degrees of latitude, whose average slope is about $E^{-2.3}$ (Aharonian et al. 2005, 2006a). The HESS detection of high energy $\gamma$ rays from fourteen new sources has improved significantly the knowledge of both the spatial distribution and the spectra and fluxes of VHE $\gamma$-ray galactic sources. These HESS results make it possible to estimate with unprecedented precision the contribution of unresolved sources to the Galactic diffuse emission recently extended to TeV energies by Milagro. In fact, the Milagro sensitivity to point sources is about $10^{-11}$ photons cm$^{-2}$ s$^{-1}$ for $E > 1$ TeV and it is of the order of the brightest integral source flux detected by HESS. Sources like the ones detected by HESS are then unresolved by Milagro and contribute to the diffuse emission Milagro measures.

Here, based on HESS results, knowing the sensitivity and the field of view of an experiment, we estimate the number of expected sources and their expected VHE $\gamma$-ray flux. We then evaluate the contribution of unresolved sources to the diffuse $\gamma$-ray emission for Milagro. The estimate of the diffuse emission arising from unresolved sources will be a lower limit.
In fact, HESS has mostly detected extended sources. For sources larger than the angular resolution of the experiment the source size determines the sensitivity of the instrument. The sensitivity decreases if the extension of the source increases. In Fig. 1 the HESS source fluxes and the sensitivity as a function of the source extensions are plotted. A clustering of sources about HESS survey sensitivity of 3 percent of the Crab flux reported in (Aharonian et al. 2005) is evident, meaning that there are probably many more to be detected with better sensitivity.

Fig. 1.— The HESS source fluxes and the HESS survey sensitivity versus source extensions are plotted (Aharonian et al. 2006a). A clustering of the sources about the HESS sensitivity limit is evident.

2. Galactic spatial distributions of PSRs and SNRs and their VHE counterparts

Hereafter the following notations will be used. In terms of the heliocentric distance $D$, the longitude $l$ and the latitude $b$ the galactocentric distance, $r$, is defined as

$$r = \sqrt{z^2 + (r_0^2 + D^2 - 2r_0D \cos(l))}$$ (1)

where $r_0 = 8.5$ kpc is the distance from the Earth to the Galactic center. The height $z$ over the Galactic Plane is

$$z = D \sin(b)$$ (2)

In the inner Galaxy region observed by HESS the existence of 91 SNRs and 389 pulsars was already known at lower energies (Green 2004; Manchester et al. 2005). Many of these
SNRs and pulsars within the inner Galaxy might emit VHE $\gamma$ rays but only a few $\gamma$ ray sources were previously known. Although the HESS Collaboration indicates a clear positional coincidence of its sources with a known SNR or pulsar only in a limited number of cases, the distribution of Galactic latitude of the seventeen VHE $\gamma$ ray sources detected by HESS agrees quite well with the distributions of all SNRs catalogued by [Green 2004] and of all pulsars catalogued by [Manchester et al. 2005]. Assuming, for example, that SNRs are a single class of counterparts with isotropic luminosity $1.95 \times 10^{34}$ erg s$^{-1}$ to the new HESS sources and taking for them a simple radiative model, [Aharonian et al. 2006a] found that the location of these sources favours a scale height of less than 100 pc, consistent with the hypothesis that these sources are either SNRs or pulsars in a massive star forming region. Therefore although for only a few of HESS sources a firm identification with counterparts at other wavelengths exists, there are some suggestions that many of the HESS sources might coincide with supernova remnants (SNRs) or pulsar wind nebulae (PWNe). In fact two of the HESS sources have SNRs as counterparts, and five of these most recently discovered HESS sources are associated with pulsar wind nebulae [Funk 2007]. SNRs are an established source class in VHE $\gamma$ ray astronomy. Possible correlations between SNRs and unidentified EGRET and HESS sources have been proposed since the release of the first EGRET catalogue [Sturmer & Dermer 1995; Esposito et al. 1996], and later for the third EGRET catalogue by [Romero et al. 1999; Combi et al. 2001]. PWNe formed from young pulsars with age less than a million years are considered as potential gamma-ray emitters [Manchester 2005]. Though a young age is not a sufficient condition for a pulsar to generate a PWN. The spin-down energy loss is the key parameter to determine whether a young energetic pulsar forms a PWN [Gotthelf 2003]. The ratio between $\gamma$-ray loud versus $\gamma$-ray quiet pulsars is uncertain. Gotthelf (2003) suggests that all pulsars with $dE/dt > dE/dt c = 3.4 \times 10^{36}$ erg/s are X-ray bright, manifest a distinct pulsar wind nebula (PWN), and are associated with a supernova event. By studying the Chandra data on the 28 most energetic pulsars of the Parkes Multibeam Pulsar Survey [Manchester 2005] Gotthelf (2004) found that 15 pulsars with $\dot{E} > 3.4 \times 10^{36}$ ergs/s are X-ray bright, show a resolved PWN, and are associated with evidence of a supernova event. This suggests that about 2.5 per cent of the radio loud pulsar have a PWN and might emit $\gamma$-rays.

Supernova remnants and pulsars are the radio counterparts of two of the high energy gamma ray candidates, SNRs and PWNe, and their spatial distribution is known from many observations at radio wavelengths. The pulsar surface density $\sigma_{PSR}(r)$, plotted in Fig. 21 is fitted by the following shifted Gamma function [Yusifov & Kuciuk 2004; Lorimer et al. 2004, 2006]

$$\sigma_{PSR}(r, z) = a \left( \frac{r}{r_0} \right)^b e^{-c \frac{(r-r_0)}{r_0}}$$

(3)

where $a = 41$ kpc$^{-2}$ and $b = 1.9$ and $c = 5.0$. For the $z$ distribution we use the exponential
function

\[ n_{\text{PSR}}(z) = d e^{-|z|/e} \]  

(4)

where \( d = 0.75 \) and \( e = 0.18 \text{kpc} \) (Lorimer et al. 2006). The SNR surface density, plotted in Fig. 2, is (Green 2004; Case & Bhattacharya 1998)

\[ \sigma_{\text{SNR}}(r) = \begin{cases} \sigma_{0_{\text{SNR}}} \sin \left( \frac{\pi r}{r_2} + \theta_0 \right) e^{-\beta r} & \text{for } r < 16.8 \\ 0 & \text{for } r > 16.8 \end{cases} \]

(5)

with \( \sigma_{0_{\text{SNR}}} = 1.96 \pm 1.38 \text{kpc}^{-2} \), \( r_2 = 17.2 \pm 1.9 \text{kpc} \), \( \theta_0 = 0.08 \pm 0.33 \) and \( \beta = 0.13 \pm 0.08 \). For the \( z \) distribution we use the exponential function

\[ n_{\text{SNR}}(z) = d e^{-|z|/e} \]  

(6)

where \( d = 0.58 \) and \( e = 0.083 \text{kpc} \) (Xu et al. 2005). Assuming the SNR and PSR distributions plotted in Fig 2, the Galaxy should contain 217 SNRs and 13176 PSRs.

For the number-intensity relation for HESS sources

In order to perform a study of the collective properties of HESS source population the number-intensity relation, \( \log N(S) - \log S \), is here used. The number-intensity relation has the advantage of using the flux data without any assumption on the distance and luminosity.

Fig. 2.— Pulsar and SNR surface distributions versus galactocentric radius \( r \) from Lorimer et al. (2006) and from Green (2004) and Case & Bhattacharya (1998), respectively.
In fact for many of HESS sources the location and luminosity are unknown. The number-intensity relation also gives information on the geometry of the volume in which the sources are contained if a uniform source distribution is assumed. Deviation from a simple power law $N \propto S^{-\alpha}$ with slope $-1$ (for the case of a thin disk) means that the sources or their luminosity function are not spatially uniformly distributed.

The major difficulties in the study of the collective properties of the HESS source population consist of the limited number of sources detected and the relatively small range of flux covered by the survey. Also, the HESS survey of the Galaxy was not performed with uniform sensitivity. In fact, whereas the sensitivity of the survey of the Galactic Plane in Galactic latitude is rather flat in the region between $-1.5$ and $1.5$ degrees, its effective exposure and therefore its sensitivity is not uniform in longitude. Longer observation times were dedicated by HESS to locations in the Galactic plane close to where three sources, HESS J1747-218 and HESS J1745-290 (in the Galactic Center), and HESS J1713-397, were already known. The average sensitivity of the survey as a function of the longitude and the latitude are shown in Fig. 2 and Fig. 3 of Aharonian et al. (2006a), respectively. In some locations of the Galaxy the survey was done at peak sensitivity of 2 per cent of the Crab flux. From Fig. 3 of Aharonian et al. (2006a) one can deduce that in order for our sample to be complete, only sources detected with more than 6 per cent the Crab flux within $-2^\circ < l < 2^\circ$ can be included. Table 1 lists the eleven sources included to plot the number-intensity relation. HESS source fluxes have small statistical errors, whereas their systematical uncertainties are about 30 per cent of the absolute value of the flux. In order to account for the large
Table 1: HESS sources included in the logN-logS with fluxes above 6 per cent of the Crab flux. All fluxes for $E > 200$ GeV are in units of in $10^{-12}$ photons cm$^{-2}$ sr$^{-1}$ s$^{-1}$ [Aharonian et al. (2006a)].

| SOURCE NAME     | FLUX ABOVE 200 GeV |
|-----------------|---------------------|
| HESSJ1614 − 518| 57.8 ± 7.7          |
| HESSJ1616 − 508| 43.3 ± 2.0          |
| HESSJ1632 − 478| 28.7 ± 5.3          |
| HESSJ1634 − 472| 13.4 ± 2.6          |
| HESSJ1640 − 465| 20.9 ± 2.2          |
| HESSJ1702 − 420| 15.9 ± 1.8          |
| HESSJ1804 − 216| 53.2 ± 2.0          |
| HESSJ1813 − 178| 14.2 ± 1.1          |
| HESSJ1825 − 137| 39.4 ± 2.2          |
| HESSJ1834 − 087| 18.7 ± 2.0          |
| HESSJ1837 − 069| 30.4 ± 1.6          |

systematic uncertainties in the fluxes a Monte-Carlo based procedure is adopted to generate the errors for the $\log N(> S) − \log S$ diagram, plotted in Fig. 4. A random number spanning an interval equal to the systematic and statistical errors in quadrature around the flux value is generated. By repeating the procedure many times standard deviations can be evaluated [Bignami & Caraveo (1980)]. These standard deviations are the error bars in the $\log N − \log S$ diagram plotted in Fig. 4. The power law fitting curve has a slope $−1.0 ± 0.1$ with reduced $\chi^2 = 0.5$ for the HESS sample for integral fluxes bigger than $S_1 = 12 \times 10^{-12}$ cm$^2$ s$^{-1}$, which corresponds to 6 per cent of the Crab flux. The number-intensity relation is

$$N(> S) = (152 ± 41) \left( \frac{S}{S_0} \right)^{(-1.0±0.1)} \quad (7)$$

where $S_0 = 10^{-12}$ cm$^2$ s$^{-1}$. The reduced $\chi^2$ for a fit with slope -1.5 would be 3.3. By assuming a tridimensional isotropic distribution of sources the slope of the number-intensity relation should be -1.5. The fact that the slope is about -1 means that the source decrease in the flux with distance is counterbalanced by the density of sources depending on the inverse square of the distance. The HESS-like sources are distributed in a thin disk, in a volume that is
larger than the visibility limit.

Fig. 4.— The number-intensity relation, \( \log N(> S) - \log S \), for HESS source population. In order to have a complete sample, only sources detected above 6 per cent of the Crab flux are included. The population of sources is distributed in a thin disk.

### 3.1. Predictions

The \( \gamma \)-ray flux due to the HESS source population above 6 per cent of the Crab flux in the region \(-30^{\circ} < l < 30^{\circ} \) and \(-2^{\circ} < l < 2^{\circ} \) is

\[
F(E > 200 \text{GeV}, -30 < l < 30, -2 < b < 2) = \int_{S_1}^{S_2} N(> S) \, dS = 2.5 \times 10^{-10} \text{ photons cm}^{-2} \text{ s}^{-1},
\]

(8)

where \( S_2 = 57.8 \times 10^{-12} \text{ cm}^2 \text{ s}^{-1} \) is the maximum flux detected by HESS from a source.

From the PSR and SNR distributions plotted in Fig.(2) there are 84 SNRs and 5324 PRSs in the region \(-30^{\circ} < l < 30^{\circ} \) and \(-2^{\circ} < b < 2^{\circ} \), whereas in the Milagro region \((40^{\circ} < l < 100^{\circ} \) and \(-5^{\circ} < b < 5^{\circ} \) there are 36 SNRs and 1358 PSRs. Assuming that supernova remnants and pulsars are the radio counterparts of high energy gamma ray sources, SNRs and PWNe, the Milagro region has 26 percent of the sources which are in the HESS region. Also, the Milagro Galactic diffuse emission is measured for a threshold energy of about 3.5 TeV, whereas the flux from unresolved sources calculated in Eq.(8) refers to the HESS threshold energy of 200 GeV. In order to estimate the contribution of unresolved sources to Milagro diffuse emission the flux in Eq.(8) has to be corrected for the different
threshold energy. All HESS sources are fitted by a power law spectrum

$$\Phi(E, \Gamma) = \Phi_0 \left( \frac{E}{1\text{TeV}} \right)^{-\Gamma},$$

and the average spectral index is $\Gamma = 2.32$. By correcting the flux in Eq. (8) for the Milagro threshold energy the flux which HESS-like sources contribute is

$$F(E > 3.5\text{TeV}, 40 < l < 100, -5 < b < 5) = 0.26 F(E > 200\text{GeV}, -30 < l < 30) \times \left( \frac{E_{\text{Milagro}}}{E_{\text{HESS}}} \right)^{(-\Gamma+1)} = 8.3 \times 10^{-12} \text{photons cm}^{-2}\text{sr}^{-1}\text{s}^{-1}. \quad (10)$$

The contribution of HESS source population amounts to at least 10 per cent of the diffuse flux which Milagro measures above 3.5 TeV. This is a lower limit for the contribution of unresolved sources to Milagro diffuse emission, as only sources above 6 percent of the Crab flux were taken into account to estimate it.

The Galactic diffuse emission measured by Milagro can be used to constrain the minimum flux $S_{\text{min}}$ below which the logN-logS plot becomes flat in order not to overproduce the Milagro flux

$$\int_{S_{\text{min}}}^{S_2} dS \frac{dN}{dS} < 7.3 \times 10^{-11} \text{photons cm}^{-2}\text{sr}^{-1}\text{s}^{-1}. \quad (11)$$

$S_{\text{min}}$ cannot be less than $1 \times 10^{-16} \text{photons sr}^{-1}\text{cm}^{-2}\text{s}^{-1}$ in order not to violate the constraint in Eq. (11).

From the number-intensity relation for HESS source population it is possible to deduce the number of sources which HESS, VERITAS, Milagro and HAWC will detect. The number of SNRs and PWNs expected for HESS if its entire field of view is scanned with a uniform sensitivity of 2 per cent of the Crab flux above 200 GeV is about 43 ± 10. If VERITAS will survey the Northern sky in the region between $30^\circ < l < 220^\circ$ and $-10^\circ < b < 10^\circ$ reaching the level of 1 per cent of the Crab flux above 100 GeV, it should detect approximately 35 ± 10 sources. Milagro has previously observed the Northern sky with a sensitivity equal to about 65 per cent the Crab flux at 3.5 TeV. At this level of sensitivity one should expect no detection of sources for Milagro and indeed no detection of sources was claimed in Atkins et al. (2005) with the data accumulated after the first three years of operation. Now after six years of data have been accumulated Milagro has reached a sensitivity equal to about 20 per cent of the Crab flux at 20 TeV median energy and should be able to detect 3 ± 1 sources. The Milagro
Collaboration has recently published the survey of the Northern sky in the region between $30^\circ < l < 220^\circ$ and $-10^\circ < b < 10^\circ$ at a threshold of 20 TeV and a threshold sensitivity of about 20 percent of the Crab detecting 4 sources \cite{Abdo}. The number of sources detected is in agreement with our predictions. After only one year of operation the proposed experiment HAWC will have surveyed the region of the sky with longitude $5^\circ < l < 110^\circ$ and $130^\circ < l < 250^\circ$ and latitude $-10^\circ < b < 10^\circ$ at 30mCrab sensitivity above 1 TeV and should have detected $19 \pm 5$ HESS-like SNRs and PWNe. The predictions given here for Milagro and HAWC are valid unless the source spectra steepen or cut-off below the Milagro threshold. However, for the sources detected by HESS the spectrum is predominantly well characterized by a single power law.

4. Alternative method to estimate the contribution of unresolved sources to the diffuse emission

Thanks to the logN-logS relation we obtained a lower limit for the contribution of unresolved HESS-like sources to the diffuse emission measured by Milagro. Here we will assume that the density of VHE $\gamma$-ray source candidates, SNRs and PWNe, follows the volume density of SNRs or of pulsars in the Galactic Plane as observed at radio wavelengths and their luminosity function is a power law, and we will then estimate their contribution to the Milagro diffuse emission.

Since the data on HESS sources are too sparse to constrain their luminosity function, we will leave it as a parametrised input. The luminosity function $\Phi(L)$ will be a power law with different indices $\alpha$ varying between -1 and -2

$$\Phi(L) = \frac{dN}{dL_\gamma} = c \left( \frac{L_\gamma}{L_{\gamma 0}} \right)^\alpha.$$  \hspace{1cm} (12)

The assumed luminosity function will then be compared with the HESS source counts to fix the normalisation $c$. In Eq. (12) $L_{\gamma 0} = 1 \times 10^{34} \text{erg/s}$. The range in luminosities for the HESS sources, for which the distance and thus the luminosity is known, varies between $10^{31} \text{erg/s}$ and $10^{36} \text{erg/s}$. In fact, most sources of $\gamma$-ray in the Galaxy are located close to the plane of the Galaxy, within a region which extends from $D_{\text{min}} = 0.3$ kpc up to $D_{\text{max}} = 30$ kpc \cite{Swordy}. The range in luminosity for the HESS sample can then be found from the HESS sensitivity (we assume 6 percent of the Crab flux) and the maximum flux detected by HESS, which are respectively

$$L_{\gamma\text{min}} = \frac{\Gamma - 1}{\Gamma - 2} E_{\text{th}} 4 \pi D_{\text{min}}^2 f_{\text{min}} = 3 \times 10^{31} \text{erg/s}$$
\[ L_{\gamma_{\text{max}}} = \frac{\Gamma - 1}{\Gamma - 2} E_{\text{th}} 4\pi D_{\text{max}}^2 f_{\text{max}} = 1 \times 10^{36} \text{erg/s} \]  

(13)

where \( E_{\text{th}} \) is the detector threshold energy and \( \Gamma \) is the spectral index if the \( \gamma \)-ray emission is a power law. By requiring that the following integral over HESS field of view and over the luminosity range given in Eq. (13) gives the number of sources HESS detects above 6 percent of the Crab flux we will obtain the normalisation factor \( c \)

\[ N(L_{\gamma_{\text{min}}}, L_{\gamma_{\text{max}}}, V) = \int_{V_{\text{HESS}}} dV \int_{L_{\gamma_{\text{min}}}}^{L_{\gamma_{\text{max}}}} dL \frac{dN_{\text{sources}}}{dV dL} = 11 \]

\[ \int_{V_{\text{HESS}}} dV \int_{L_{\gamma_{\text{min}}}}^{L_{\gamma_{\text{max}}}} dL \rho_{\text{sources}}(r, z) c \left( \frac{L_{\gamma}}{L_{\gamma_{0}}} \right)^{\alpha} \]

\[ \int_{0.3}^{30} dD D^2 \int_{-30}^{30} dl \int_{-2}^{2} db \sin(b) \rho_{\text{sources}}(l, b, D) \int_{L_{\gamma_{\text{min}}}}^{L_{\gamma_{\text{max}}}} dL c \left( \frac{L_{\gamma}}{L_{\gamma_{0}}} \right)^{\alpha} . \]

(14)

In Eq. (14) \( \rho_{\text{sources}} \) is the density of SNRs and PWNe.

4.1. Predictions

The integral flux above \( E_0 \) from resolved and unresolved sources from a region in the Galaxy which extends from \( D_{\text{min}} \) to \( D_{\text{max}} \) in heliocentric distance, from \( b_{\text{min}} \) to \( b_{\text{max}} \) in latitude and from \( l_{\text{min}} \) to \( l_{\text{max}} \) in longitude is

\[ F(E > E_0, l_{\text{min}} < l < l_{\text{max}}, b_{\text{min}} < b < b_{\text{max}}) = \int_{0}^{L_{\gamma_{\text{max}}}} dL_{\gamma} \Phi(L_{\gamma}) F(L_{\gamma}, D) dN_{\text{sources}}(r, z) \]

\[ = \int_{0}^{L_{\gamma_{\text{max}}}} dL_{\gamma} \Phi(L_{\gamma}) F(L_{\gamma}, D) \int dV \sigma_{\text{sources}}(r) n_{\text{sources}}(z) \]

\[ = \int_{0}^{L_{\gamma_{\text{max}}}} dL_{\gamma} \Phi(L_{\gamma}) F(L_{\gamma}, D) \int_{D_{\text{min}}}^{D_{\text{max}}} dD D^2 \int_{l=l_{\text{min}}}^{l=l_{\text{max}}} dl \int_{b=b_{\text{min}}}^{b=b_{\text{max}}} db \sin(b) \rho(l, b, d) \]

(15)
where

$$F(L_{\gamma}, D) = \frac{\Gamma - 2}{\Gamma - 1} \frac{1}{4\pi D^2 E_{th}} L_{\gamma}$$  \hspace{1cm} (16)$$

If the luminosity function defined in Eq. (12) has slope $\alpha = -1$ the total flux from resolved and unresolved PWNe divided over the HESS field of view if 2.5 per cent of radio loud pulsars emit $\gamma$-rays is

$$F_{PW\,N}(E > 200 GeV, -30 < l < 30, -3 < b < 3) = 1.3 \times 10^{-9} \text{ photons cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}.$$  \hspace{1cm} (17)$$

The total flux from the Galactic SNR population is

$$F_{SNR}(E > 200 GeV, -30 < l < 30, -3 < b < 3) = 1.1 \times 10^{-9} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$  \hspace{1cm} (18)$$

For $\alpha = -1$ the integral flux expected for the Milagro field of view from HESS-like sources assuming a pulsar shaped surface density if 2.5 per cent of radio loud pulsars emit $\gamma$-rays is

$$F_{PW\,N}(E > 200 GeV, 40 < l < 100, -5 < b < 5) = 4.6 \times 10^{-10} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$  \hspace{1cm} (19)$$

while the contribution from SNRs shaped surface density is

$$F_{SNR}(E > 200 GeV, 40 < l < 100, -5 < b < 5) = 4.4 \times 10^{-10} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$  \hspace{1cm} (20)$$

The fluxes in Eq. (19) and (20) are lower than the HESS fluxes from resolved and unresolved sources. In fact, as shown in Fig. 3, HESS observes the inner region of the Galaxy, whereas Milagro field of view is more spread toward the outer regions in the Galaxy, where the number of sources is substantially lower, so a lower contribution from unresolved sources is expected for Milagro’s region of the Galactic plane than for HESS.

The integral flux from unresolved pulsars if 2.5 per cent of radio loud pulsars emit $\gamma$-rays corrected for the Milagro threshold becomes

$$F_{PW\,N}(E > 3.5 \text{ TeV}, 40 < l < 100) = F_{PW\,N}(E > 200 \text{ GeV}, 40 < l < 100) \times \left(\frac{E_{Milagro}}{E_{HESS}}\right)^{(-\Gamma+1)} = 3.6 \times 10^{-11} \text{ photons cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}.$$  \hspace{1cm} (21)$$
whereas the contribution from SNRs is

$$F_{SNR}(E > 3.5 \text{TeV}, 40 < l < 100) = F_{pulsar}(E > 200 \text{GeV}, 40 < l < 100) \times \left(\frac{E_{\text{Milagro}}}{E_{\text{HESS}}}\right)^{(-\Gamma+1)} = 3.4 \times 10^{-11} \text{photons cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$$

(22)

where $E_{\text{Milagro}}$ and $E_{\text{HESS}}$ are the Milagro and HESS energy thresholds, respectively. Assuming a slope $\alpha = -1$, for the luminosity function and summing the two contributions from HESS-like SNRs and PWNe, the emission due to unresolved sources to the Milagro diffuse emission is comparable to the diffuse emission itself. If the slope of the luminosity function $\alpha = -1.5$ the contribution of unresolved SNRs and PWNe to the diffuse emission measured by Milagro is about 5 percent and for $\alpha = -2$ this contribution becomes negligible, which is in disagreement with the lower limit of 10 percent for the contribution of HESS-like sources to the VHE diffuse emission previously found. Thus the slope of the luminosity function for HESS-like sources is constrained to be $-1 > \alpha > -1.5$.

5. Conclusions

The number-intensity relation and the luminosity function for the HESS source population were investigated using the assumption that HESS sources are distributed as PSRs and SNRs detected at radio wavelengths. In order for the chosen sample of sources to be complete only the HESS sources with fluxes above 6 percent of the Crab flux were taken into account to derive the number-intensity relation. The contribution of unresolved HESS-like sources to the diffuse emission measured by Milagro was also estimated. Using the logN-logS relation for the HESS sample of Galactic $\gamma$-ray emitters at least 10 percent of the diffuse emission at TeV energies is estimated to be due to the contribution of unresolved HESS-like sources. This result is a lower limit for such a contribution because we have taken into account only sources detected above 6 percent of the Crab flux and because HESS sensitivity gets worse for extended sources, meaning that some extended sources might have been missed by HESS. Using the logN-logS relation we have also predicted the number of HESS-like sources which VERITAS, HESS and HAWC should detect during their survey of the sky. An alternative procedure to evaluate the contribution of unresolved HESS-like sources to Milagro diffuse emission gives the diffuse flux due to unresolved sources comparable to the diffuse emission itself. We finally constrained the slope of the luminosity function. The main uncertainty of
this calculation consists in assuming that the distribution of γ-ray sources follows the distribution of either pulsars or SNRs observed in the radio. In particular, in order to predict how many PSRs observed in the radio have a PWN and are possible gamma ray emitters we used the result that the spin-down energy loss \( dE/dt > dE/dt_c = 4 \times 10^{36} \text{erg/s} \) for a young energetic pulsar to form a PWN. In this respect we have ignored the existence of pulsars, such as Geminga, which are γ-ray loud, yet not observed in the radio.

New observational results support the hypothesis that a population of unresolved sources contribute significantly to the emission at very high energy. Milagro has recently reported the discovery of TeV gamma ray emission from the Cygnus Region of the Galaxy, which exceeds the predictions of conventional models of gamma-ray production \( \text{[Abdo et al.] 2007}\) from the same region in the Galaxy where the Tibet Array has detected an excess of cosmic rays \( \text{[Amenomori et al.] 2006}\). Thanks to its improved sensitivity Milagro has also better imaged the whole Northern sky and discovered four sources and four source candidates \( \text{[Abdo et al.] 2007}\). HESS has seen very high energy emission spatially correlated with giant molecular clouds located in the Galactic Center \( \text{[Aharonian et al.] 2006b}\). The energy spectrum measured by HESS close to the Galactic Center is \( E^{-2.3} \), significantly harder than the \( E^{-2.7} \) spectrum of the diffuse emission and equal to the average spectrum of the HESS source population. The emission from the Galactic Center might possibly unveil a cosmic ray accelerator.

To draw more definitive conclusions about the very high energy γ-ray sky, new observations are of fundamental importance. New hints will be provide by both MAGIC and VERITAS, which already survey the Cygnus Region. Finally GLAST will investigate the window of energy between 10 MeV to 300 GeV, covering the energy gap left between EGRET and the ground-based low threshold gamma-ray observatories.

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