CAN THE DIFFUSE EMISSION DETECTED BY MILAGRO BE GIVEN BY THE SUM OF FLUXES OF UNRESOLVED POINT SOURCES ?

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We tried to figure out if Milagro detection of diffuse emission from the Galaxy could be produced by the sum of fluxes of unresolved sources. To this end we considered HESS latest paper, reporting the detection of eight new TeV γ-ray sources from the galactic plane. [1]

HESS is an array of telescopes using imaging Cherenkov technique. Its sensitivity around the energy threshold of 200 GeV is below 1 per cent of the Crab flux (1.75×10^{-11} cm^{-2} s^{-1}) for long exposures and its angular resolution better than 0.1 degrees. HESS scans the inner part of the Galaxy in the region between -30 and +30 degrees in galactic longitude ($-30 < l < 30$) and between -3 and +3 degrees in galactic latitude ($-3 < b < 3$). HESS has recently reported the detection of 10 sources close to the Galactic Plane. Eight of these sources were previously unknown. All new HESS sources are located close to the Galactic Plane, within -1 and 0 degrees of latitude (see Fig 1). The sum of all fluxes from HESS 10 resolved sources is $\times 10^{-10}$ cm^{-2} s^{-1} per $E > 200GeV$. Given that HESS results are correct we can make a rough prediction on the number of sources Milagro should be able to see from the Galactic plane and on the expected flux from these sources to be compared with Milagro diffuse emission flux. Assuming all sources have the same intrinsic luminosity, the flux F from a source depends upon the distance D of the detector as

$$F \propto \frac{1}{D^2} \tag{1}$$

and inverting

$$D \propto \sqrt{\frac{1}{F}}\,. \tag{2}$$

By differentiating Eq.(2)

$$dD \propto \frac{1}{2}\,F^{-3/2}\,dF \tag{3}$$

we obtain the number of sources on the galactic plane as function of the flux up to a constant k

$$dN_{sources} = 2\,k\,\pi\,D\,dD = \pi\,k\,F^{-2}dF\,. \tag{4}$$

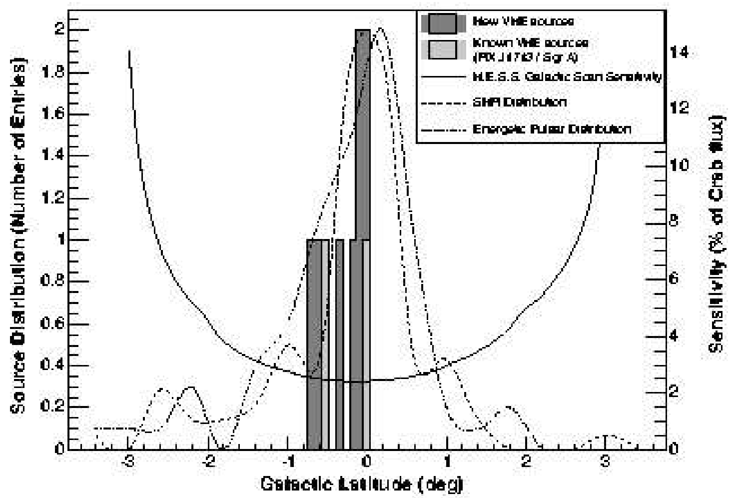


Figure 1: *Latitude distribution of 10 HESS sources.[1]*

Integrating Eq.(4) over all source fluxes above HESS sensitivity, about $6 \times 10^{-12}\ cm^{-2}\ s^{-1}$ for $E > 200\,GeV$, the number of sources detected by HESS fixes the constant k

$$\int_{6\times10^{-12}}^{2\times10^{-11}} dN_{sources} = \int_{6\times10^{-12}}^{2\times10^{-11}} \pi\, k\, F^{-2} dF = 10\,. \tag{5}$$

From Eq.(5) $k = \frac{8.6\times10^{-11}}{\pi} s^{-1}$. Milagro sensitivity is around $10^{-11}\ cm^{-2}\ s^{-1}$ for $E > 1TeV$. Milagro sensitivity is, in fact, of the order of the maximum integral flux detected by HESS [1]. Therefore we expect Milagro to resolve no point sources.

The region in the Galaxy, where point sources are, extends from $D_{min} =$ 0.3 kpc up to $D_{max} = 30$ kpc [2]. Assuming that the flux from each source depends only upon the distance from the detector $F = F(D)$ and not on the type of source, HESS total flux from resolved and unresolved sources is

$$F_{sources\,HESS} \quad = \quad \int_{D_{min}}^{D_{max}} F(D)\, dN_{sources}$$

$$
\begin{aligned}
&= \int_{D_{min}}^{D_{max}} \frac{k}{D^2}\, 2\,\pi\, D\, dD \\
&= 2\,\pi\, k\, ln \frac{D_{max}}{D_{min}} = 7.9 \times 10^{-10} cm^{-2}\, s^{-1}\,.
\end{aligned}
\tag{6}
$$

If we assume the spectrum for HESS sources to be

$$\Phi(E) = \Phi_0\, (\frac{E}{1TeV})^{-2.2} \tag{7}$$

and we integrate over the energy from HESS threshold at 0.2 TeV up to infinity

$$\int_{0.2}^{\infty} dE\, \Phi(E) = \int_{0.2}^{\infty} dE \Phi_0\, (\frac{E}{1\, TeV})^{-2.2} = 7.9 \times 10^{-10} cm^{-2}\, s^{-1} \tag{8}$$

we obtain that the normalization $\Phi_0 = 1.4 \times 10^{-10} cm^{-2} s^{-1} TeV^{-1}$. Milagro threshold energy is higher and the predicted flux from unresolved sources would be

$$\int_{1}^{\infty} dE\, \Phi(E) = \int_{1}^{\infty} dE \Phi_0\, (\frac{E}{1\, TeV})^{-2.2} = 1.2 \times 10^{-10} cm^{-2}\, s^{-1}\,. \tag{9}$$

Eq.(9) implies that Milagro integral flux F from a source depends upon the distance D of the detector as

$$F \propto \frac{k'}{D^2} \tag{10}$$

where the constant $k' = \frac{1.3}{\pi} \times 10^{-11} s^{-1}$ is obtained from Eq.(5). Assuming the following spectrum for the sources

$$\Phi(E) = \Phi_0\, (\frac{E}{1TeV})^{-2.6} \tag{11}$$

and integrating it over the energy from 0.2 TeV up to infinity

$$\int_{0.2}^{\infty} dE\, \Phi(E) = \int_{0.2}^{\infty} dE \Phi_0\, (\frac{E}{1\, TeV})^{-2.6} = 7.9 \times 10^{-10} cm^{-2}\, s^{-1} \tag{12}$$

$\Phi_0 = 1.0 \times 10^{-10} cm^{-2} s^{-1} TeV^{-1}$. Milagro threshold energy is higher and the predicted flux from sources in this case would be

$$\int_{1}^{\infty} dE\, \Phi(E) = \int_{1}^{\infty} dE \Phi_0\, (\frac{E}{1\, TeV})^{-2.6} = 0.6 \times 10^{-10} cm^{-2}\, s^{-1}\,, \tag{13}$$

and $k' = \frac{0.7}{\pi} \times 10^{-11} s^{-1}$.

On the other hand Milagro galactic diffuse emission is $5.1 \times 10^{-10}\ cm^{-2}\ s^{-1}\ sr^{-1}$. Since Milagro phase space is 600 degrees Milagro diffuse galactic flux is $5.1 \times 10^{-10}\, 600\, (\frac{\pi}{180})^2 = 1 \times 10^{-10}\ cm^{-2}\ s^{-1}$. The predicted total source flux in Eq.(9) and Eq.(13) and Milagro galactic diffuse flux are thus comparable. Could we then conclude that Milagro claimed diffuse galactic emission is produced by the sum of point sources ? To make a more realistic comparison of HESS and Milagro fluxes we calculate the flux due to all sources, essentially pulsars and SNRs, for HESS and Milagro, specifying how these sources are distributed on the plane of the Galaxy. Indeed HESS is looking at 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. We do not consider the latitude distributions of pulsars and SNRs. Most point sources are, in fact, located close to the plane of the Galaxy, within a region ($-2 < b < 2$), to which both Milagro and HESS have access. (see Fig.1)

In terms of the heliocentric distance D and the longitude angle l the galactocentric distance, r, is [3]

$$r = \sqrt{r_0^2 + D^2 - 2\, r_0\, D\, cos(l)} \tag{14}$$

with $r_0 = 8.5\ kpc$. (see Fig.(2)).

The pulsar surface density $\rho_{pulsar}(r)$ is fitted by the following shifted Gamma function [4]

$$\rho_{pulsar}(r) = A\, (\frac{x}{x_0})^a\, e^{[-b\, (\frac{x - x_0}{x_0})]} \tag{15}$$

where $x = r + r_1$ and $x_0 = r_0 + r_1$, $A = 37.6 \pm 1.9\ kpc^{-2}$, $a = 1.64 \pm 0.11$, $b = 4.01 \pm 0.24$ and $r_1 = 0.55 \pm 0.10\ kpc$. The SNR surface density is [5, 6]

$$\begin{aligned} \rho_{snr}(r) &= A\, sin(\frac{\pi\, r}{r_2} + \theta_0)\, e^{-\beta r} \quad for \quad \mathrm{r} < 16.8 \\ \rho_{snr}(r) &= 0 \quad for \quad \mathrm{r} > 16.8 \end{aligned}$$

with $A = 1.96 \pm 1.38\ kpc^{-2}$, $r_2 = 17.2 \pm 1.9\ kpc$, $\theta_0 = 0.08 \pm 0.33$ and $\beta = 0.13 \pm 0.08$. Analogously to what we have done in Eq.(5), the total number of γ sources resolved by HESS, 10, fixes the constant k in

$$F(D) = k\, \frac{1}{D^2} \tag{16}$$

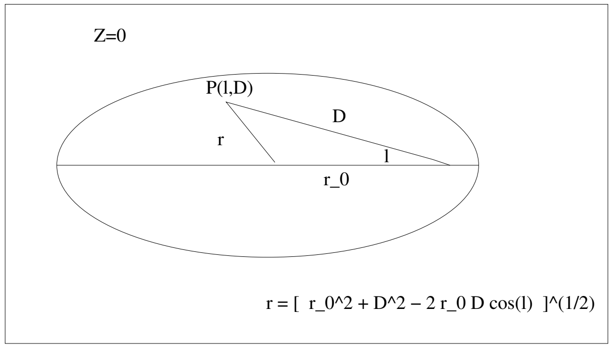


Figure 2: *Relation between galactocentric radius r, heliocentric distance D and longitude angle l on the galactic plane, z=0*

between the flux F and the distance from the detector D

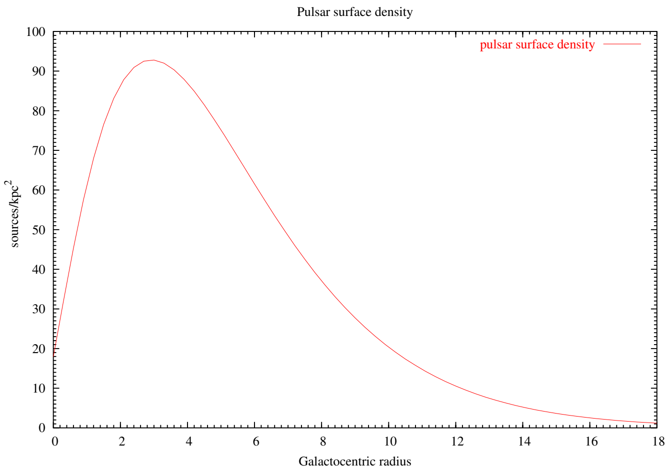
$$\begin{aligned} N_{HESS} &= \int dD\, D \int dl\, (\rho_{pulsar}(l,D) + \rho_{snr}(l,D)) = 10 \\ &= \int_{6\times10^{-12}}^{20\times10^{-12}} dF\, k\, F^{-2} \int_{-30}^{30} dl\, (\rho_{pulsar}(l,F) + \rho_{snr}(l,F)) = 10 \end{aligned}$$

where $D = \sqrt{\frac{k}{F}}$. The constant $k = 2.0 \times 10^{-12} s^{-1}$. With respect to our previous calculation, we have now implemented the distribution of pulsars and SNRs in the Galaxy over HESS field of view. Assuming that the flux from each source in the galactic plane varies exclusively because of the distance from the detector, the total flux from the 10 point sources for HESS above 200 GeV is

$$\begin{aligned} F_{sourcesHESS} &= \int_{0.3}^{30} dD\, D\, F(D) \int_{-30}^{30} dl\, (\rho_{pulsar}(l,D) + \rho_{snr}(l,D)) \\ &= \int_{0.3}^{30} dD\, D\, \frac{k}{D^2} \int_{-30}^{30} dl\, (\rho_{pulsar}(l,D) + \rho_{snr}(l,D)) \\ &= 5.4 \times 10^{-10} cm^{-2} s^{-1}\,, \end{aligned}$$

whereas the integral flux expected for Milagro from point sources for $E > 200 TeV$ GeV is

$$\begin{aligned} F_{sourcesMilagro} &= \int_{0.3}^{30} dD\, D\, F(D) \int_{40}^{100} dl\, (\rho_{pulsar}(l,D) + \rho_{snr}(l,D)) \\ &= \int_{0.3}^{30} dD\, D\, \frac{k}{D^2} \int_{40}^{100} dl\, (\rho_{pulsar}(l,D) + \rho_{snr}(l,D)) \\ &= 3.2 \times 10^{-10} cm^{-2} s^{-1}\,, \end{aligned}$$



By correcting for the Milagro energy threshold the integral flux from unresolved sources $F_{sources\,Milagro}$ is $0.5 \times 10^{-10} cm^{-2} s^{-1}$ (if the differential γ-ray flux is $\propto E^{-2.2}$) and $0.2 \times 10^{-10} cm^{-2} s^{-1}$ (if the differential γ-ray flux is $\propto E^{-2.6}$). Milagro diffuse emission integral flux above $E > 1TeV$ is $1.0 \times 10^{-10} cm^{-2} s^{-1}$. We can conclude that the contribution from unresolved point sources to Milagro diffuse emission is between 20 and 50 per cent of Milagro diffuse emission. Nonetheless compared to the flux due to all 10 sources resolved by HESS, Milagro diffuse emission is 10 per cent.

$\Phi(E)$	Diffuse emission	Unresolved sources (Uniform distributions)	Unresolved sources (Pulsar and SNR distributions)
$E^{-2.2}$	1.0	1.2	0.5
$E^{-2.6}$	1.0	0.6	0.2

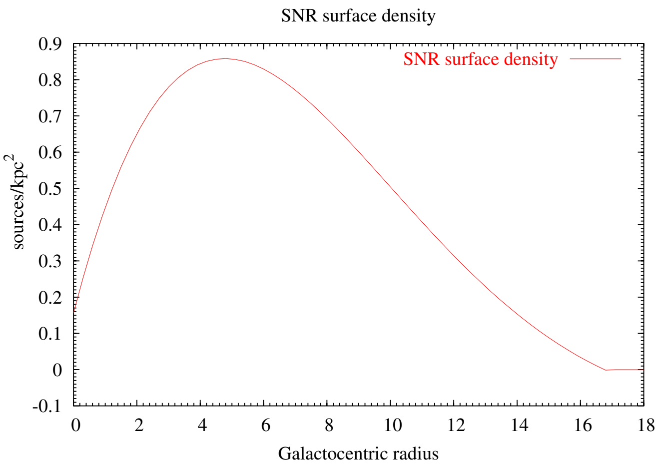
Table 1. *Summary of Milagro diffuse emission integral flux and fluxes due to unresolved sources. All fluxes are expressed in* $10^{-10} cm^{-2} s^{-1}$.

References

[1] Aharonian et al, *Science 307,1938-1942* 2005

[2] Swordy, *28th International Cosmic Ray Conference, Universal Academy Press Inc.* 2003

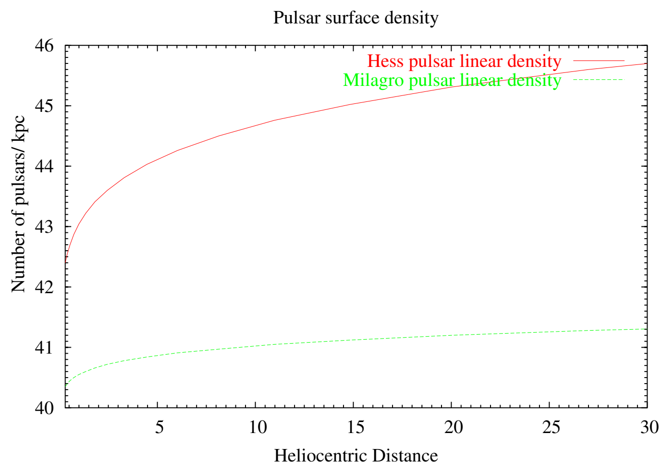
[3] Schlickeiser, *Cosmic ray Astrophysics, Springer Verlag*, 2002

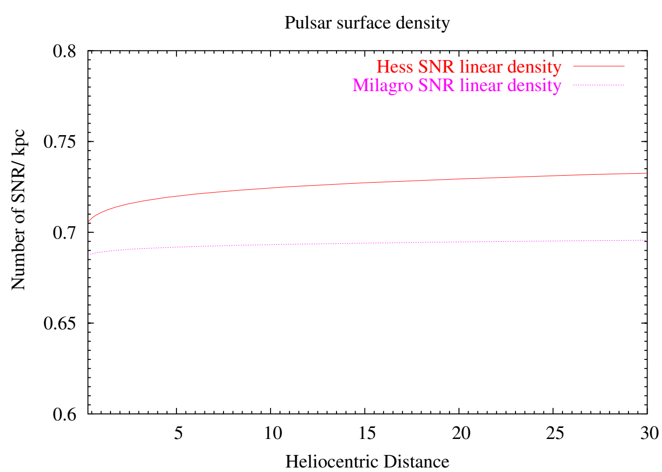


[4] Yusifov and Kücük *AA 422, 545-553*, 2004

[5] Case and Bhattacharya *ApJ 504, 761-772*, 1998

[6] Green *Bull.Astr.Soc.India, 32, 335-370*, 2004


Pulsar surface density
Hess pulsar linear density
Milagro pulsar linear density
Number of pulsars/ kpc
Heliocentric Distance
46
45
44
43
42
41
40
5
10
15
20
25
30


Pulsar surface density
Hess SNR linear density
Milagro SNR linear density
Number of SNR/ kpc
Heliocentric Distance
0.8
0.75
0.7
0.65
0.6
5
10
15
20
25
30

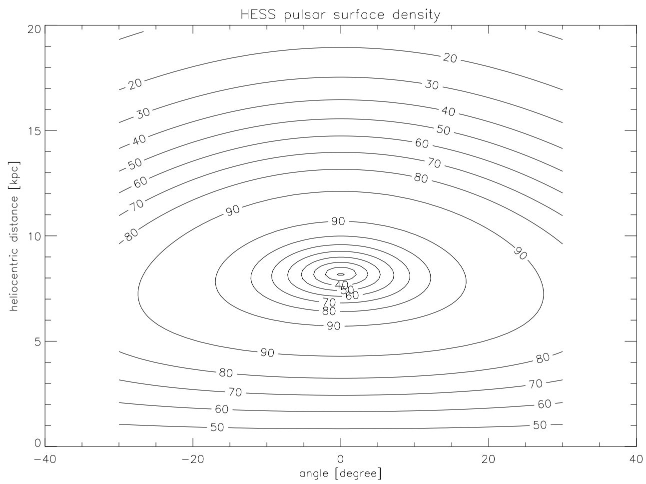


Figure 3: *Contour plot of Hess pulsar distribution*

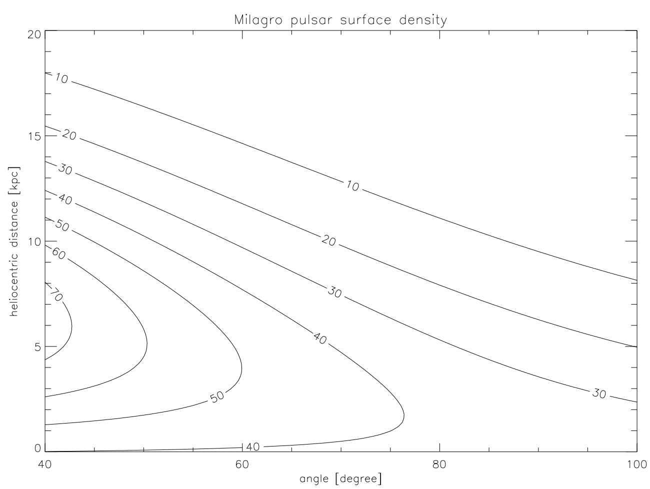


Figure 4: *Contour plot of Milagro pulsar distribution*

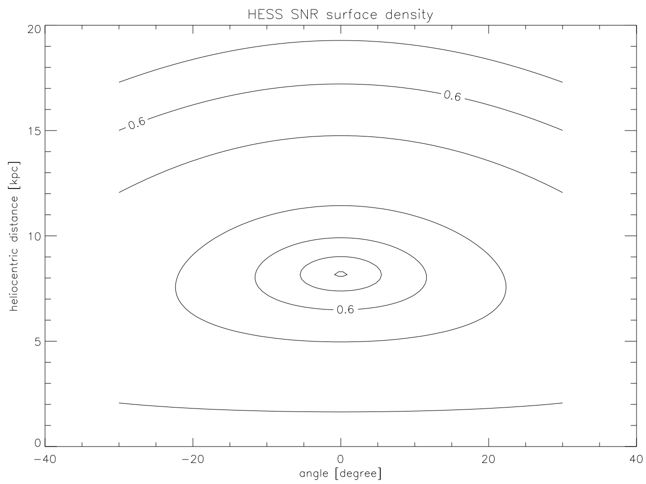


Figure 5: *Contour plot of HESS SNR distribution*

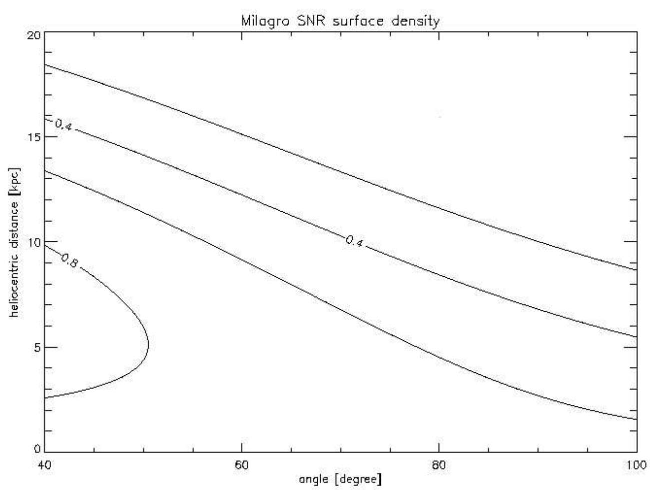


Figure 6: *Contour plot of Milagro SNR distribution*

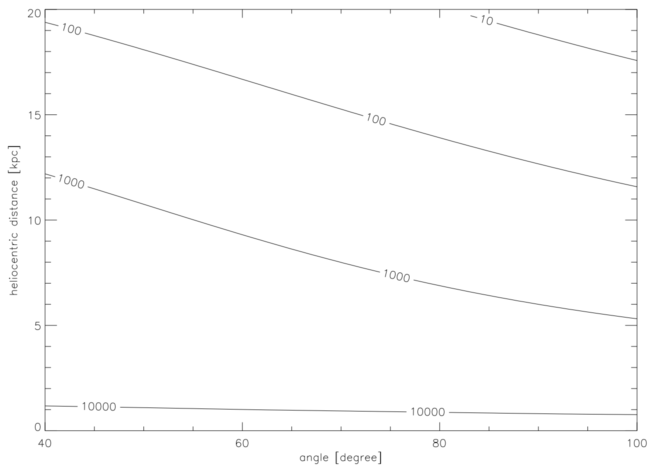


Figure 7: *Contour plot of Milagro integral γ-ray flux from pulsars in* $10^{-15} cm^{-2} s^{-1}$ *(*$\Phi \propto E^{-2.2}$*)*

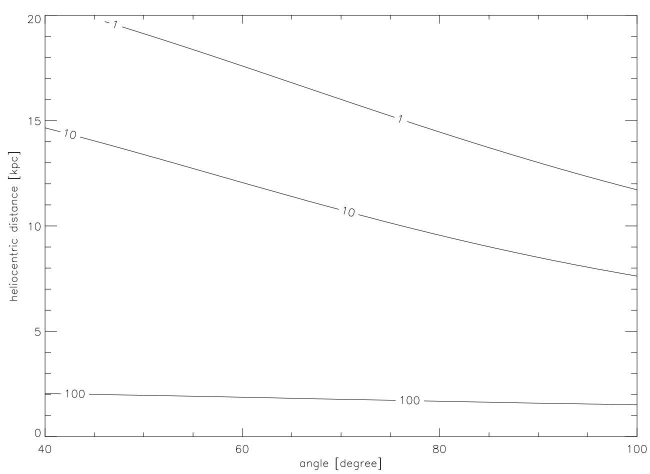


Figure 8: *Contour plot of Milagro integral γ-ray flux from SNRs in* $10^{-15} cm^{-2} s^{-1}$ *(*$\Phi \propto E^{-2.2}$*)*

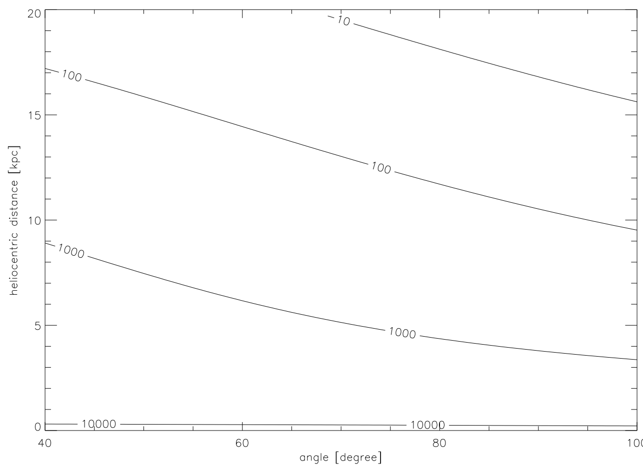


Figure 9: *Contour plot of Milagro integral γ-ray flux from pulsars in* $10^{-15} cm^{-2} s^{-1}$ *(*$\Phi \propto E^{-2.6}$*)*

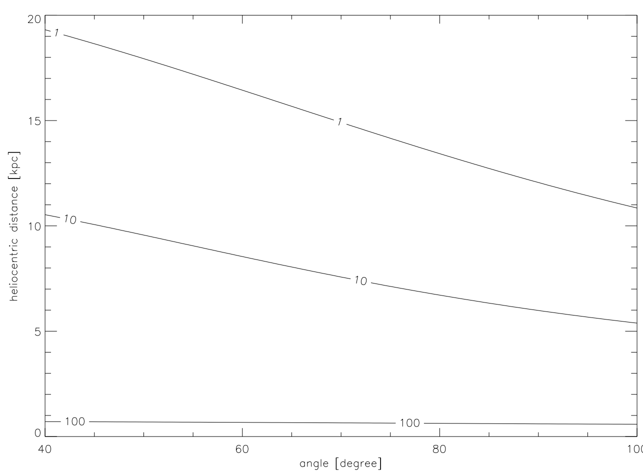


Figure 10: *Contour plot of Milagro integral γ-ray flux from SNRs in* $10^{-15} cm^{-2} s^{-1}$ *(*$\Phi \propto E^{-2.6}$*)*