DIFFUSION OF COSMIC RAYS AND THE GAMMA-RAY LARGE AREA TELESCOPE: PHENOMENOLOGY AT THE 1–100 GeV REGIME

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ABSTRACT

This paper analyzes astrophysical scenarios that may be detected at the upper end of the energy range of the Gamma-Ray Large Area Space Telescope (GLAST), as a result of cosmic-ray (CR) diffusion in the interstellar medium (ISM). Hadronic processes are considered the source of γ-ray photons from localized molecular enhancements nearby accelerators. Two particular cases are presented: (1) the possibility of detecting spectral energy distributions (SEDs) with maxima above 1 GeV, which may be constrained by detection or nondetection at very high energies (VHES) with observations by ground-based Cerenkov telescopes, and (2) the possibility of detecting V-shaped, inverted spectra, due to collision of a nearby (to the line of sight) arrangement of accelerator/target scenarios with different characteristic properties. We show that finding these signatures (in particular, a peak at the 1–100 GeV energy region) indicates the underlying mechanism producing the γ-rays that is realized by nature, which accelerator (age and relative position to the target cloud) and under which diffusion properties CRs propagate.

Subject headings: gamma rays: observations — gamma rays: theory

Online material: color figures

1. INTRODUCTION

A total of 1506 cosmic photons with energies above 10 GeV were detected during the 9 year lifetime of the Energetic Gamma-Ray Experiment Telescope (EGRET; Thompson et al. 2005). Of this number, 187 photons were found within 1° of sources listed in the Third EGRET Catalog (Hartman et al. 1999) and can be plausibly related to the more energetic extent of the cataloged EGRET sources. The majority of the remaining photons correspond to diffuse Galactic and extragalactic radiation, albeit this conclusion is based on the similarity of their spatial and energy distributions to the diffuse model. No significant time clustering nor source shining only at such high energies was detected. The scarcity of these detections represents the least electromagnetic window that remains to be opened between already explored energy ranges. EGRET was hampered in performing detailed studies of the γ-ray sky above 10 GeV, due to backplash of secondary particles produced by high-energy γ-rays causing a self-veto in the monolithic anticoincidence detector used to reject charged particles and due to a noncalibrated detector response. GLAST, soon to be launched, will not be strongly affected by these problems, since the anticoincidence shield was designed in a segmented fashion (Moiseev et al. 2007). The effective area of GLAST will be roughly an order of magnitude larger than that of EGRET, leading to an increased sensitivity for detecting celestial γ-ray photons (see Fig. 1 of Funk et al. 2008). GLAST’s default observing plan is a grid survey mode open the gate to the possible discovery of new phenomenology. This paper analyzes astrophysical scenarios that can be detected at the upper end of the energy range of GLAST as a result of cosmic-ray (CR) diffusion in the ISM.

2. THE ROLE OF DIFFUSION

The π0-decay γ-ray flux from a source of proton density \( n_p \) is given by

\[
F(E_\gamma) = 2 \int_{E_p}^{\infty} F_\gamma(E_p) \frac{dE_p}{\sqrt{E_p^2 - m_e^2}} dE_\gamma,
\]

where \( E_p^{\text{min}} \) is the minimum pion energy given by \( E_\gamma^{\text{min}}(E_\gamma) = E_\gamma + m_e^2/4E_\gamma \), and

\[
F_\gamma(E_p) = 4\pi n_p \int_{E_p}^{E_p^{\text{min}}} J_p(E) \frac{d\sigma_{\gamma\gamma}(E_p,E_p)}{dE_p} dE_p,
\]

where \( d\sigma_{\gamma\gamma}(E_p,E_p)/dE_\gamma \) is the differential cross section for the production of π0 of energy \( E_p \) by a proton of energy \( E_p \) in a p-p collision. For a study of different parameterizations of this cross section (see, e.g., Domingo-Santamaria & Torres 2005; Kelner et al. 2006). The limits of integration in the last expression are obtained by kinematic considerations (e.g., Torres 2004). We have implicitly neglected any possible gradient of CR or gas number density in the target. The CR spectrum is given by \( J_p(E,r,t) = (c\beta/4\pi)f \), where \( f(E,r,t) \) is the differential number density of protons at an instant \( t \) and distance \( r \) from the source. Just for comparison, the spectrum of cosmic rays in the Earth vicinity is (e.g., Dermer 1986). \( J_p(E) = 2.2(E/\text{GeV})^{-2.75} \text{cm}^{-2} \text{s}^{-1} \text{GeV}^{-1} \text{sr}^{-1} \). The particle’s differential number density \( f \) satisfies the radial-temporal-energy–dependent diffusion equation

\[
\frac{df}{dt} = [D(E)/r^2] (\partial f/\partial r)^2 + \partial f/\partial E\frac{P}{f} + Q,
\]

where \( P = -dE/dt \) is the energy-loss rate of the particles, \( Q = Q(E,r,t) \) is the source function, and \( D(E) \) is the diffusion coefficient, for which we assume a dependence on the particle’s energy. The energy-loss rate is due to ionization and nuclear
interactions, for which the timescale is $\tau_{pp}$, with the latter dominating over the former energies larger than 1 GeV. The nuclear loss rate is $P_{\text{nuc}} = E/\tau_{pp}$, where $\tau_{pp} = (n_p \sigma_{\text{pp}})/\kappa$ is the timescale for the corresponding nuclear loss, where $\kappa \sim 0.45$ is the inelasticity of the interaction, and $\sigma_{\text{pp}}$ is the cross section.

Aharonian & Atoyan (1996) presented a solution for the diffusion equation with an arbitrary diffusion coefficient and impulsive injection spectrum $f_{\text{inj}}(E)$, such that $Q(E, r, t) = N_0 f_{\text{inj}}(E) \phi(t)$. For the particular case in which $D(E) \propto E^\alpha$ and $f_{\text{inj}} \propto E^{-\beta}$, it reads

$$f(E, r, t) \sim (N_0 E^{-\alpha} / \pi^{3/2} R_{\text{dif}}^3) \exp \left[ -(\alpha - 1) t / \tau_{pp} - (R / R_{\text{dif}})^2 \right],$$

where

$$R_{\text{dif}} = 2 \sqrt{D(E) t \left( \exp(\delta t / \tau_{pp}) - 1 \right) / \tau_{pp}}$$

stands for the radius of the sphere up to which the particles of energy $E$ have time to propagate after their injection. In case of continuous injection of accelerated particles, $Q(E, t) = Q_0 E^{-\alpha} T(t)$, the previous solution needs to be convolved with the function $T(t) = \Theta(t)$, for times $t$ less than the energy-loss time, $f(E, r, t) = \left[ Q_0 E^{-\alpha} / 4 \pi D(E)^{1/2} \right] \int_{R_{\text{dif}}}^\infty e^{-x^2} dx$ (Atoyan et al. 1995). We assume typical values, $\alpha = 2.2$ and $\delta = 0.5$.

In the case of energy-dependent propagation of CRs, a large variety of $\gamma$-ray spectra is expected (e.g., Aharonian & Atoyan 1996; Gabici & Aharonian 2007; Torres et al. 2008). Diffusion of CRs has also been explored as an explanation for the high-energy observations of the Galactic center (e.g., Hinton & Aharonian 2007). We have systematically studied, by numerically producing over 2000 $E^2 F$ distributions, the dependences with the parameters involved. Table 1 summarizes the results for both an impulsive and a continuous accelerator. The influence of the total energy injected by the accelerator as CRs ($W_p$), the age of the accelerator ($t$), the medium density in which the CRs propagate ($n$), the diffusion coefficient of the medium (given at 10 GeV, $D_{\text{trans}}$), the distance from the accelerator to the molecular cloud where the $\gamma$-rays are produced ($R$), the density of the cloud ($n_{\text{cl}}$), its mass ($M_{\text{cl}}$) and radius ($r_{\text{cl}}$), and the distance of such a system to the observer ($d$) are described. The dominant dependences are related to the age of the accelerator and the diffusion coefficient. These parameters both impact the CR distribution. The faster the diffusion, the farther the target can be from the accelerator and still be subject to a significantly enhanced CR spectrum; see Figure 1. We use a source (cloud) parameterized in units of $M_{\odot} = M_{\text{cl}} / 10^5 M_{\odot}$ and $d_{\text{kpc}} = d/1$ kpc. The age $t_{\text{trans}}$, defined in the case of an impulsive accelerator, is that at which the timescale for the corresponding nuclear loss becomes comparable to the age of the accelerator itself. $D_{\text{trans}}$ is the value of the diffusion coefficient for which the SEDs stop displacing in energy, keeping approximately the same flux as inferred from Figure 1.

Setting, as an example, reasonable parameters for the energy injected by the accelerator into cosmic rays (e.g., $W_p = 5 \times 10^{46}$ ergs for an impulsive source and $L_p = 5 \times 10^{37}$ ergs s$^{-1}$ for a continuous one) and for the interstellar medium density (e.g., $n = 1$ cm$^{-3}$), we have found several scenarios for the appearance of hadronic maxima produced by diffusion. Examples are shown in Figure 2 for the two types of accelerators. We have found that two kinds of peaks in this energy regime are possible, those that are not detected by an instrument with the sensitivity of EGRET or MAGIC and those that are not detected by an instrument such as H.E.S.S. or VERITAS (the latter are not shown in the examples in Fig. 2). We also note that the impulsive accelerator produces steeper maxima. We find that maxima in the SED, hadronically produced as an effect of diffusion of CRs, are possible and not uncommon at the high-energy end, where they produce $\gamma$-radiation at a level of flux detectable by the Large Area Telescope (LAT).

Figure 3 shows as contour plots the energy at which the maximum of the SED is found for the cases of impulsive acceleration of cosmic rays at different distances, ages of the accelerator, and diffusion coefficients. The energy-dependent propagation effects underlying our expectations for the diffusion of CRs in the

### Table 1: Dependence of the SED ($E^2 F$ versus $E$) on the Different Parameters

| Parameter and Meaning | Effect on the $E^2 F$ Distributions versus $E$ |
|-----------------------|-----------------------------------------------|
| $W_p$, total energy injected for the accelerator as CRs | Imp.: overall scaling, small effects in the range if in the typical range $10^{35}$ to $10^{40}$ ergs. |
| $L_p$, energy injected per unit time | Cont.: overall scaling, small effects in the range if in the typical range $10^{37}$ to $10^{38}$ ergs s$^{-1}$. |
| Increasing $t$, age of the accelerator | Imp.: peak displaces to smaller energies for a fixed distance, until $t > t_{\text{trans}}$, and the peak displaces to smaller fluxes. |
| Cont.: peak displaces to smaller energies and larger fluxes, for a fixed distance. |

Interstellar Medium

Increasing $D_{\text{cl}}$, the diffusion coefficient of the medium (at 10 GeV),...

Negligible effects in the typical range $0.5-10$ cm$^{-3}$, since $t_{pp} \gg t$.

For a fixed age, curve displaces to smaller energies until $D_{\text{cl}} > D_{\text{trans}}$, where peaks generated by clouds at large separation, $R$, displace up and peaks generated by clouds at smaller $R$ displace down in the SED.

For a fixed distance, curve displaces to smaller energies and larger fluxes, for a fixed distance. Peaks generated by older accelerators (larger $t$) displace down and peaks generated by younger accelerators (smaller $t$) displace up.

Notes.—Imp. (cont.) stands for the impulsive (continuous) accelerator case. Dependences on cloud parameters such as density ($n_{\text{cl}}$), mass ($M_{\text{cl}}$), and radius ($r_{\text{cl}}$) are obvious and related.
studied parameter space are clearly depicted there. The diffusion radius for $t \ll \tau_{pp}$ is $R_{\text{diff}}(E) = 2 [D(E)t]^{1/2}$, so that at a fixed age and distance, only particles of higher energy will be able to compensate for a smaller $D_{10}$, producing SED maxima at higher $E$-values. The smaller values of $D_{10}$ that we study are expected in dense regions of the ISM (e.g., Ormes et al. 1988; Torres et al. 2008). It is interesting to note that for many, albeit not for all, of the SEDs studied, the maximum in $E^2F$ space is found at energies beyond the energetic range of GLAST. On the other hand, we also note that using Figure 3 to interpret a GLAST observational

Fig. 1.— SEDs generated by CR propagation in ISM with different properties. Fluxes correspond to a cloud with $M_5/d_{25}^2$ = 0.5. Curves for $D_{10} = 10^{26}, 10^{27}$, and $10^{28}$ cm$^2$ s$^{-1}$ are shown with solid, dotted, and dashed lines, respectively. Sensitivities of EGRET (red) and GLAST (blue), H.E.S.S. (magenta; survey mode and pointed observations with typical integrations), and MAGIC (yellow) are shown for comparison (see Fig. 1 of Funk et al. [2008] for details on sensitivities). [See the electronic edition of the Journal for a color version of this figure.]

Fig. 2.— Examples of the model predictions for a hadronic maximum in the 1–100 GeV regime. Left: Predictions for a cloud scaled at $M_5/d_{25}^2 = 0.025$, located at 20 pc from an accelerator of $10^4$ yr and diffusing with $D_{10} = 10^{27}$ cm$^2$ s$^{-1}$. Right: Predictions for a cloud scaled at $M_5/d_{25}^2 = 0.08$ located at 10 pc from an accelerator of $10^3$ yr and diffusing with $D_{10} = 10^{28}$ cm$^2$ s$^{-1}$. As the the ratio $M_5/d_{4pc}^2$ increases, the curves move up, maintaining all other features. [See the electronic edition of the Journal for a color version of this figure.]
The discovery of a 1–100 GeV maximum provides interesting clues to the nature of the astrophysical system that generates the Č-rays. First, we find these SEDs in cases in which the scenario does not predict detectable emission at the EGRET sensitivity, so they represent new phenomenology. Second, we see from Figure 3 that the range of accelerator-target separations and ages of the accelerator that would produce such a 1–100 GeV maximum is rather limited (see in Fig. 3 the narrow contours for maxima at such energies), which would lead to a direct identification of the source, in case such a system is found in the vicinity of the GLAST detection.

We now focus on the case of one unresolved but composite GLAST source. We thus consider two separate accelerator-cloud complexes that are close to the line of sight such that GLAST observes them as a single source, within its point-spread function (PSF). This kind of scenario would yield the observational signature of an inverted spectrum. Figure 4 shows four possible inverted spectra. The two figures in the top (bottom) part are generated by an impulsive (continuous) accelerator. The SED characterizing the oldest (youngest) accelerator is shown by dashed (dot-dashed) lines in each of the scenarios. Even if EGRET could have been able to weakly detect some of the inverted source models we simulated, it could not conclusively relate it to such a phenomenon, due to its large low-energy PSF. The counterpart at higher energies is a bright source potentially detectable by ground-based telescopes. Due to continuous energy coverage, GLAST is a prime instrument for tracking this phenomenology. The right panels show particular examples in which the detection of the source by an instrument with the sensitivity of EGRET is not possible at all. The inverted spectrum is less deep in these scenarios. Less pronounced V-shaped spectra can be obtained with concomitantly lower fluxes at TeV energies.

3. SOLUTION VALIDITY AND TIMESCALES

Essentially, if we use the equations given above to compute Č-ray fluxes, we are assuming that there is no significant cosmic-ray gradient in the target (i.e., the gamma-ray emissivity is constant throughout the cloud). This assumption may be valid when the size of the cloud is less than the distance to the accelerator and the diffusion coefficients inside and outside the cloud are not significantly different (or even if they are, the proton-proton timescale is larger than the time it takes for cosmic rays to overtake the whole cloud).

Here we did not parameterize on the mass of the cloud, but rather on the value of $M_\odot d_{kpc}^2$, i.e., the mass of the cloud in units of $10^{6} M_\odot$ divided by the distance squared in kpc, which we now call $A$ for brevity. In order for the solutions to apply, then, two conditions need to be satisfied, $\tau_{pp} > t$ and the size of the cloud $r_{cl}$ (or simply $r$ below) has to be such that $r_{cl} < R$ (see Table 1 to refresh the meaning of variables, and do not confuse $r$, the size of the cloud, with $R$, the separation between the cloud and the accelerator). The density of the cloud, presented in terms of $A$, is $n_{cl} = 10^6 A d_{kpc}^2 / r^3$, cm$^{-3}$. The nuclear loss rate is $\tau_{pp} \sim 100 r_{pc} / (A d_{kpc}^2)$ yr. The second condition (i.e., $r < R$) would be immediately satisfied if, say, $r = R/x$, where $x > 1$. Then, an astrophysical scenario (not unique!) that also fulfills the first condition ($\tau_{pp} > t$) is found when $B = ((100/A)[R^2/(x^3)])^{1/2} > d_{kpc}$. To be viable, of course $d_{kpc} < 8$ kpc, which can be used to define a minimum value of $x$, given a specific model with fixed $A$, $R$, and $t$. A final check can be done by comparing that the density obtained by replacing the previous inequalities, $n_{cl} < (10^6/t_{pp})$ cm$^{-3}$, is in the range found in molecular clouds (which, for the ages considered, is always fulfilled). Table 2 shows the configurations used in the different figures of our work, together with the
minimum value of $x$ such that $r < R_{pp}$, $t > t_{pp}$, and $d_{pc} < 8$ are all maintained and the solutions used are applicable.

It is also interesting to discuss the different timescales within the cloud (see Gabici et al. 2007). In the former work, it was shown that dynamical and advection cloud timescales do not play a relevant role in this problem. To estimate the degree of cloud penetration by cosmic rays, it suffices to compare the loss and diffusion timescales. The former was derived above. The latter can be written as

$$
\tau_{\text{cl-dif}} = 725 \xi \left( \frac{10^{27}}{D_{10}} \right) \left( \frac{r_{pc}}{5} \right) \left( \frac{E}{\text{GeV}} \right)^{-0.5} \left( \frac{B}{10 \mu G} \right)^{0.5},
$$

where the diffusion coefficient inside the cloud has been parameterized as

$$
D_{\text{cl}}(E) = 3.1 \xi D_{10} \left( \frac{E}{\text{GeV}} \right)^{0.5} \left( \frac{B}{10 \mu G} \right),
$$

where $\xi < 1$ would account for a possible suppression of the diffusion coefficient inside the cloud as compared with that of the environment. For the proton-proton timescale to be larger than the time it takes for cosmic rays to overtake the whole cloud, following the notation above and taking an average cloud magnetic field of $10 \mu G$, the following condition applies:

$$
\frac{R}{xAd_{pc}^2} \frac{D_{10}}{10^{27} \text{ cm}^2 \text{ s}^{-1}} \frac{D_{10}}{10^{27} \text{ cm}^2 \text{ s}^{-1}} > 0.29 \frac{B}{10 \mu G} \left( \frac{E}{\text{GeV}} \right)^{0.5},
$$

TABLE 2

| Model | $M_{5}/d_{pc}$ | $R_{pc}$ | $t_{yr}$ | $x_{min}$ |
|-------|----------------|---------|---------|-----------|
| Figure 1 | 0.5 | 10 | $10^3$ | 1.4 |
| | 0.5 | 10 | $10^5$ | 0.2 |
| | 0.5 | 100 | $10^3$ | 14.6 |
| | 0.5 | 100 | $10^5$ | 3.1 |
| Figure 2, left | 0.025 | 20 | $10^4$ | 3.6 |
| Figure 2, right | 0.08 | 10 | $10^3$ | 2.7 |
| Figure 4, top left | 0.01 | 5 | $4 \times 10^3$ | 0.3 |
| | 0.1 | 20 | $2 \times 10^4$ | 1.8 |
| Figure 4, top right | 3 | 100 | $2 \times 10^6$ | 0.6 |
| | 0.1 | 15 | $4 \times 10^3$ | 2.4 |
| Figure 4, bottom left | 0.004 | 15 | $2 \times 10^6$ | 0.9 |
| Figure 4, bottom right | 0.017 | 40 | $2 \times 10^6$ | 1.4 |
| | 2.5 | 30 | $6 \times 10^4$ | 0.7 |
With the parameters summarized in Table 2, it can be shown that plenty of clouds exist such that the diffusion timescale is shorter than the energy-loss one at all energies and especially at the ones we focus on at the higher end of \textit{GLAST}, and so we can neglect this effect. In general, our values of \(A\) and typical galactic distances make for not so massive clouds, and in general our values of \(R\) make for not so large clouds. In this situation, only for a low diffusion coefficient (e.g., \(10^{26} \text{ cm}^2 \text{ s}^{-1}\)), timescales could become comparable if \(\xi < 1\), but then again, no significant suppression is expected when the environment already has such a low \(D_{10}\).

4. CONCLUDING REMARKS

Compton peaks (of which the first example may already have been found; Aharonian et al. 2006) are not the only way to generate a maximum in a SED in the range 1–100 GeV. A large variety of parameters representing physical conditions in the vicinity of a CR accelerator could produce a rather similar effect. Distinguishing these cases would require multiwavelength information, searching for counterparts, and modeling. If such a maximum is interpreted hadronically, as a result of diffusion of CRs in the ISM and their subsequent interaction with a nearby target, the results herein presented, given the energy at which the maximum of the SED is reached, constrain the characteristics of the putative accelerator, promoting the identification process. Indeed, one of the most distinguishing aspects of this study is the realization that these signatures (in particular, a peak at the 1–100 GeV energy region) indicate the underlying mechanism producing the \(\gamma\)-rays that is realized by nature, which accelerator (age and relative position to the target cloud) and under which diffusion properties CRs propagate, as exemplified in Figure 3. In a survey mode such as the one \textit{GLAST} will perform, it might also be possible to observe rather unexpected, telltale SEDs, like those V-shaped ones presented here, if observed with instruments having a limited PSF, predictably leaving many Galactic sources unresolved. Indeed, we finally remark about the V-shaped spectra presented here that we have focused on the situation where \textit{from the same place in the sky} we have a double-peaked structure. If instead, two nearby sources at different energies are indeed resolvable by \textit{GLAST}, i.e., already displaced in the \textit{GLAST} range, and both are above the threshold for detection, we would have a clear case of morphological change and spatial dislocation with energy that would certainly make the study more interesting. As noted recently,\(^5\) a double peak could also be seen, coming from the same place in the sky, if we consider two populations of CRs interacting with the same cloud, for instance, the usual \(E^{-2.75}\) Galactic bath of cosmic rays (producing a photon spectrum peaking in the GeV regime) and the escaped CRs from the nearby source (producing a photon spectrum peaking in the TeV range). This possibility would, however, apply only to the case of very young accelerators, e.g., 2000 years or so, with clouds significantly separated from it, and thus it is a less general scenario than we have explored in this paper as the mechanism for V-spectra production.

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\___\footnote{In a poster by Gabici, Aharonian, and Casanova at the Gamma-2008 meeting, 2008 July 6–11, Heidelberg, and to our knowledge yet unpublished.}

REFERENCES

Aharonian, F. A., & Atoyan, A. M. 1996, A&A, 309, 917
Aharonian, F. A., et al. 2006, A&A, 448, L43
Atoyan, A. M., Aharonian, F. A., & Völk, H. J. 1995, Phys. Rev. D, 52, 3265
Dermer, C. D. 1986, A&A, 157, 223
Domingo-Santamaría, E., & Torres, D. F. 2005, A&A, 444, 403
Gabici, S., Reimer, O., Torres, D. F., & Hinton, J. A. 2008, ApJ, 679, 1299
Hartman, R. C., et al. 1999, ApJS, 123, 79
Hinton, J., & Aharonian, F. A. 2007, ApJ, 657, 302
Kelner, S. R., Aharonian, F. A., & Bugayov, V. V. 2006, Phys. Rev. D, 74, 034018
Moiseev, A. A., Hartman, R. C., Ormes, J. F., Thompson, D. J., Amato, M. J., Johnson, T. E., Segal, K. N., & Sheppard, D. A. 2007, Astropart. Phys., 27, 339
Ormes, J. F., Ozel, M. E., & Morris, D. J. 1988, ApJ, 334, 722
Thompson, D. J., Bertsch, D. L., & O’Neal, R. H., Jr. 2005, ApJS, 157, 324
Torres, D. F. 2004, ApJ, 617, 966
Torres, D. F., Rodriguez Marrero, A. Y., & de Cea del Pozo, E. 2008, MNRAS, 387, L59