

INVERSE COMPTON EMISSION FROM GALACTIC SUPERNOVA REMNANTS: EFFECT OF THE INTERSTELLAR RADIATION FIELD

TROY A. PORTER¹

Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064; tporter@scipp.ucsc.edu

IGOR V. MOSKALENKO²

Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305; imos@stanford.edu

AND

ANDREW W. STRONG

Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany; aws@mpe.mpg.de

Received 2006 June 15; accepted 2006 July 18; published 2006 August 18

ABSTRACT

The evidence for particle acceleration in supernova shells comes from electrons whose synchrotron emission is observed in radio and X-rays. Recent observations by the HESS instrument reveal that supernova remnants also emit TeV γ -rays, long-awaited experimental evidence that supernova remnants can accelerate cosmic rays up to the “knee” energies. Still, uncertainty exists whether these γ -rays are produced by electrons via inverse Compton scattering or by protons via π^0 -decay. The multiwavelength spectra of supernova remnants can be fitted with both mechanisms, although a preference is often given to π^0 -decay due to the spectral shape at very high energies. A recent study of the interstellar radiation field indicates that its energy density, especially in the inner Galaxy, is higher than previously thought. In this Letter we evaluate the effect of the interstellar radiation field on the inverse Compton emission of electrons accelerated in a supernova remnant located at different distances from the Galactic center. We show that contribution of optical and infrared photons to the inverse Compton emission may exceed the contribution of cosmic microwave background and in some cases broaden the resulting γ -ray spectrum. In addition, we show that if a supernova remnant is located close to the Galactic center, its γ -ray spectrum will exhibit a “universal” cutoff at very high energies due to the Klein-Nishina effect and not due to the cutoff of the electron spectrum. As an example, we apply our calculations to the supernova remnants RX J1713.7–3946 and G0.9+0.1, recently observed by HESS.

Subject headings: cosmic rays — Galaxy: general — gamma rays: theory —
ISM: individual (G0.9+0.1, RX J1713.7–3946) — radiation mechanisms: nonthermal —
supernova remnants

Online material: color figures

1. INTRODUCTION

A new calculation (Porter & Strong 2006) of the Galactic interstellar radiation field (ISRF) consistent with multiwavelength observations by DIRBE and FIRAS indicates that the energy density of the ISRF is higher, particularly in the inner Galaxy, than previously thought. This has implications for the inverse Compton (IC) scattering of electrons and positrons and other electromagnetic processes in the interstellar medium (Moskalenko & Strong 2000; Moskalenko et al. 2006). Another place where the enhanced ISRF may play a role is the IC emission off very high energy (VHE) electrons accelerated in a supernova remnant (SNR) shock.

SNRs are believed to be the primary sources of cosmic rays in the Galaxy. Observations of X-ray (Koyama et al. 1995) and γ -ray emission (Aharonian et al. 2005b, 2006) from SNR shocks reveal the presence of energetic particles, thus testifying to efficient acceleration processes. Acceleration of particles in collisionless shocks is a matter of intensive research in conjunction with the problem of cosmic-ray origin (Drury 1983; Blandford & Eichler 1987; Jones & Ellison 1991). Current models include nonlinear effects (e.g., Berezhko & Völk 2006) and treat particle acceleration using hydrodynamic codes (e.g., Ellison & Cassam-

Chenai 2005). The predicted spectrum of accelerated particles has a power-law form in rigidity with an index that may slightly vary around -2.0 . Conventional estimates put the maximum reachable particle energy (protons) at or just below the knee energy; for the case of electrons the maximum energy is lower due to the synchrotron and IC energy losses (Ellison & Cassam-Chenai 2005). Young SNRs may be capable of particle acceleration up to 10^{17} eV due to the effect of magnetic field amplification (Bell & Lucek 2001) around the shock and assuming Bohm diffusion and a Sedov expansion law.

The VHE γ -ray emission from shell-type SNRs has been modeled using leptonic (IC) and hadronic (π^0 -decay) scenarios (e.g., Baring et al. 2005). The leptonic scenario fits the broadband spectrum of an SNR assuming a pool of accelerated electrons scattered off the cosmic microwave background (CMB) producing VHE γ -rays, while the magnetic field and electron spectrum cutoff are tuned to fit the radio and X-ray data (e.g., Lazendic et al. 2004). The hadronic model fits the VHE γ -ray spectrum assuming a beam of accelerated protons hits a target, such as a nearby molecular cloud (Aharonian 2002). The latter, if definitively proven, would be the first experimental evidence of proton acceleration in SNRs. While there is no clear distinction between different models of VHE emission from SNRs, some authors tend to prefer the hadronic scenario since it fits better the observed spectral shape (Aharonian et al. 2006; Berezhko & Völk 2006). Such a preference, however, is made

¹ Also Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803.

² Also Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94309.

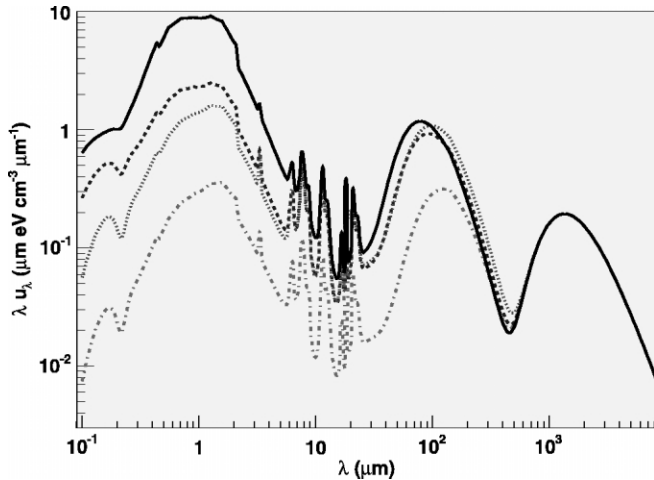


FIG. 1.—Interstellar radiation field energy density. *Solid line*: $R = 0$ kpc, $z = 0$ kpc. *Dashed line*: $R = 3$ kpc, $z = -0.05$ kpc. *Dotted line*: $R = 4$ kpc, $z = 0$ kpc. *Dash-dotted line*: $R = 7.5$ kpc, $z = 0$ kpc. [See the electronic edition of the Journal for a color version of this figure.]

based on a simplified “one-zone” model, which typically includes CMB photons only.

In this Letter we evaluate the effect of the ISRF on the IC emission of electrons accelerated in SNRs located at different distances from the Galactic center (GC). As examples, we apply our calculations to the shell-type SNR RX J1713.7–3946 and composite SNR G0.9+0.1 recently observed by the High Energy Stereoscopic System (HESS; Aharonian et al. 2005a, 2006).

2. INTERSTELLAR RADIATION FIELD

The Galactic ISRF calculation uses a model for the distribution of stars in the Galaxy, a model for the dust distribution and properties, and a treatment of scattering, absorption, and subsequent reemission of the stellar light by the dust. A brief description of our calculation is available in Moskalenko et al. (2006); we reiterate the main points here.

Our stellar model assumes a type classification based on that used in the SKY model of Wainscoat et al. (1992), with modifications to account for results from recent experiments such as the Two Micron All Sky Survey, Sloan Digital Sky Survey, and others (e.g., Ojha 2001; Juric et al. 2005), and synthetic spectral modeling studies (e.g., Girardi et al. 2002).

Dust is modeled with a mixture of polycyclic aromatic hydrocarbons, graphite, and silicate. The dust grains are spherical, and we include details of their absorption and scattering efficiencies, abundances, and size distribution in the scattering and heating calculations (Li & Draine 2001; Weingartner & Draine 2001). Stochastic and equilibrium heating of the dust grains is treated following Draine & Li (2001) and Li & Draine (2001). The dust is assumed to follow the Galactic gas distribution and metallicity gradient (Moskalenko et al. 2002; Strong et al. 2004, and references therein).

Figure 1 shows the total ISRF at the positions that we calculate the IC emission in § 3. Information on the calculation method, spatial and spectral distribution in the Galactic plane, and a brief comparison of our calculations with previous results and the locally observed ISRF are given in Moskalenko et al. (2006); further discussion of the new ISRF is deferred to a forthcoming paper (T. Porter & A. Strong 2006, in preparation).

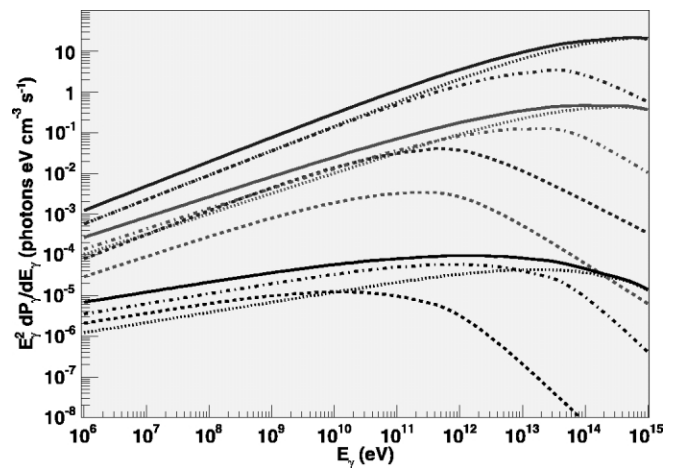
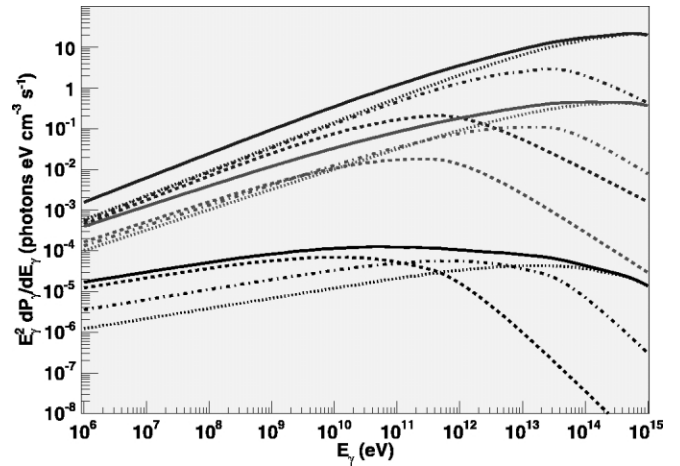


FIG. 2.—Inverse Compton emissivity in the Galactic plane for $R = 0$ kpc (*top*) and $R = 4$ kpc (*bottom*). *Solid line*: Total. *Dashed line*: Optical. *Dot-dashed line*: Infrared. *Dotted line*: CMB. For each panel, the topmost line sets correspond to $\gamma^{-1.8}$, the middle line sets correspond to $\gamma^{-2.0}$, and the bottommost correspond to $\gamma^{-2.5}$ electron spectra, respectively. [See the electronic edition of the Journal for a color version of this figure.]

3. CALCULATIONS

For an assumed isotropic ISRF and electron distribution, the IC emissivity (photons $\text{cm}^{-3} \text{s}^{-1}$) is given by

$$\frac{dP_\gamma}{d\epsilon_2} = c \int d\epsilon_1 \int d\gamma_e n_e(\epsilon_1) n_e(\gamma_e) \frac{dQ_\gamma(\gamma_e, \epsilon_1)}{d\epsilon_2}, \quad (1)$$

where $\epsilon_2 = E_\gamma/m_e c^2$ and $\epsilon_1 = \epsilon/m_e c^2$ are the dimensionless γ -ray and target photon energy, $\gamma_e = E_e/m_e c^2$ is the electron Lorentz factor, n_e and n_e are the differential target photon and electron number densities, and $dQ_\gamma/d\epsilon_2$ is given by equation (9) in Jones (1968).

To illustrate the effect of different electron spectral indices on the IC emission, we take an electron number density $n_e(\gamma_e) = n_0 \gamma_e^{-\delta}$ normalized so that $\int_{\gamma_{\min}}^{\infty} n_e(\gamma_e) d\gamma_e = 1 \text{ cm}^{-3}$ with $\gamma_{\min} = 1 \text{ MeV}/m_e c^2$ for $\delta = 1.8$, $\delta = 2.0$, and $\delta = 2.5$.

Figure 2 shows the calculated IC emissivity using the ISRF at $R = 0$ (*top*) and $R = 4$ (*bottom*) in the Galactic plane. There are two essential effects that contribute to produce the total emission curves in Figure 2. First, the variation in the electron spectral index $\delta = 1.8 \rightarrow 2.5$ increases the contribution by op-

tical and infrared (IR) photons to the γ -ray emission below ~ 50 GeV and ~ 1 TeV, respectively. As δ increases, the number of low-energy electrons increases; the IC scattering rate by these electrons off optical and IR photons becomes larger, giving more upscattered photons. In turn, as the γ -ray energy increases, the contribution by the optical and IR photons to the total emissivity decreases from the reduction of the scattering cross section in the Klein-Nishina (KN) regime. Thus, softer electron spectra promote more efficient scattering of the optical and IR components, increasing their relative contributions. Second, the density of optical and IR photons varies with position in the Galaxy. Toward the GC, the optical photon density is high, almost an order of magnitude larger per target photon energy interval when compared with the optical component at $R = 4$ kpc. Similarly, over the inner Galaxy the IR photon energy density is significantly higher than the CMB. This gives a contribution by the optical and IR photons to the total IC emission that is at least comparable to the CMB over these regions of the Galaxy.

Note that the marked decrease in the optical, then IR, and then CMB emission as the γ -ray energy increases in Figure 2 is due to the reduction of the scattering cross section in the KN regime, as described above, and not due to any cutoff we have introduced in the electron spectrum. If a cutoff was included in the electron spectrum, it would further decrease the contribution from the CMB relative to the optical and IR components (see Fig. 4).

To illustrate the effect of the ISRF in a purely leptonic scenario, we calculate the synchrotron and IC emission using a one-zone model (Aharonian & Atoyan 1999) for the SNR RX J1713.7–3946. We use an electron spectrum $Q_e(E) = Q_0 E^{-\delta} \exp(-E/E_{\max})$, where Q_0 , δ , and E_{\max} are adjustable parameters. The synchrotron emission for a magnetic field strength B is calculated using the usual formulae (Ginzburg 1979; Ghisellini et al. 1988).

Figure 3 shows the photon flux from RX J1713.7–3946 calculated for a distance of $d = 1$ kpc (top) and $d = 6$ kpc (bottom). This covers the range of distances quoted by various authors (Lazendic et al. 2004; Aharonian et al. 2006). The IC emission is calculated using the appropriate ISRF spectrum for each distance (see Fig. 1). For both cases, we reproduce the TeV emission first: with $\delta \sim 1.8$ – 2.2 and $E_{\max} \sim 15$ – 40 TeV a reasonable fit can be obtained. Next, we fit the radio and X-ray data within the constraints imposed by the TeV emission: $\delta \sim 2.0$ and $E_{\max} \sim 15$ – 25 TeV, with $B \sim 5$ – 20 μ G are allowed. The electron luminosity for an age of 1000 years ($d = 1$ kpc) or 10,000 years ($d = 6$ kpc) is $(1$ – $4) \times 10^{37}$ ergs s^{-1} , with larger luminosities for the more distant case. The parameters used are not unique. As a particular example, the values used in Figure 3 are $\delta = 2.0$, electron luminosity of 1.5×10^{37} ergs s^{-1} , $E_{\max} = 25$ TeV, and $B = 12$ μ G ($d = 1$ kpc); $\delta = 2.0$, electron luminosity of 3.5×10^{37} ergs s^{-1} , $E_{\max} = 25$ TeV, and $B = 15$ μ G ($d = 6$ kpc).

We also consider the composite SNR G0.9+0.1 observed by HESS (Aharonian et al. 2005b); this composite SNR is a source of VHE electrons, as evidenced by the synchrotron X-ray emission (Porquet et al. 2003) and is located in the GC region where the ISRF density is high. As for RX J1713.7–3946, we use a one-zone model except that we modify the source spectrum to be a broken power law with a break at energy E_{break} . As before, we adjust the electron luminosity and high-energy spectral index to fit the TeV observations; we then vary B and E_{\max} to reproduce the X-ray data. Then, E_{break} and

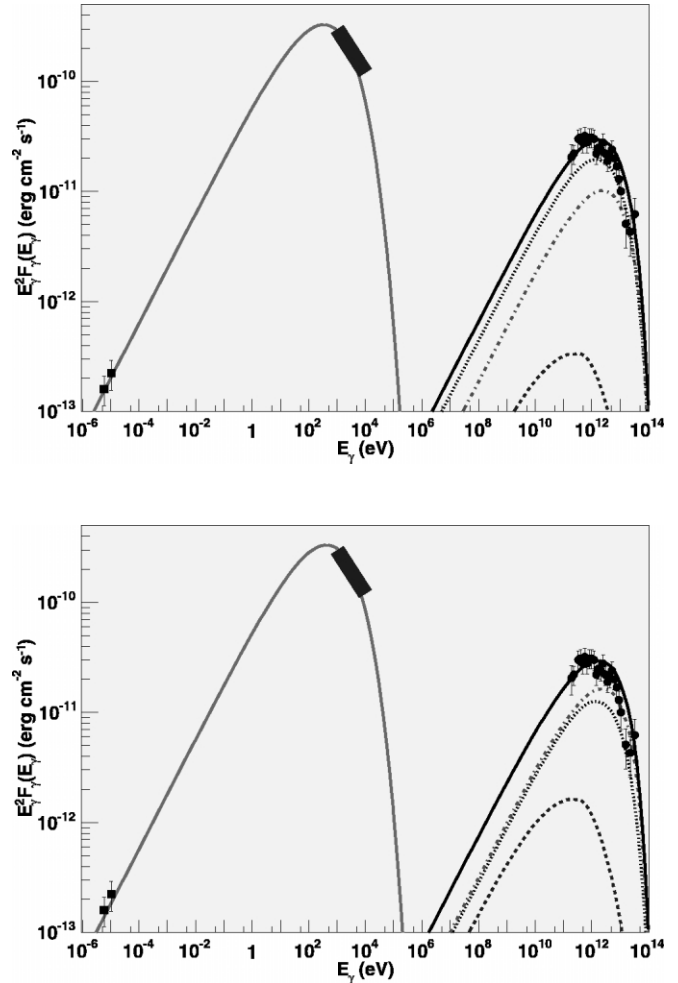


FIG. 3.—Fit to the flux spectrum of RX J1713.7–3946 using the ISRF for $d = 1$ kpc (top) and $d = 6$ kpc (bottom). Solid line: Total synchrotron and IC flux. Dashed line: Optical IC. Dash-dotted line: Infrared IC. Dotted line: CMB IC. Radio data (ATCA) from Lazendic et al. (2004) for the northwest rim of RX J1713.7–3946, but upscaled by a factor of 2 following Aharonian et al. (2006); X-ray data (ASCA) from Pannuti et al. (2003); γ -ray data (HESS) from Aharonian et al. (2006). [See the electronic edition of the Journal for a color version of this figure.]

the low-energy spectral index are adjusted to give consistency with the radio data. Figure 4 shows the calculated intrinsic photon flux for G0.9+0.1 at the GC. The parameter values are $\delta_L = 2.0$, $\delta_U = 2.8$, $E_{\text{break}} = 15$ GeV, where δ_L and δ_U are the spectral indices below and above E_{break} , respectively, $B = 9.5$ μ G, $E_{\max} = 1000$ TeV, and an electron luminosity 2.5×10^{38} ergs s^{-1} for an assumed age of 5000 years. Note that these values are again not unique, and other combinations are possible.

The cutoff in the IC emission for the optical and IR in Figures 3 and 4 comes from the reduction of the scattering cross section in the KN regime; only for the CMB is the IC spectral cutoff solely due to the cutoff in the electron spectrum. The cutoff in the IC emission for the IR in Figure 3 is only partially due to the KN effect, since the electron spectral cutoff energy is essentially lower. This effect plays an important role for an SNR close to the GC where the ISRF is dominant. In this case, the cutoff energy of the VHE γ -ray spectrum becomes universal and defined exclusively by the reduction of the scattering cross section and not by an assumed electron spectral cutoff. Note

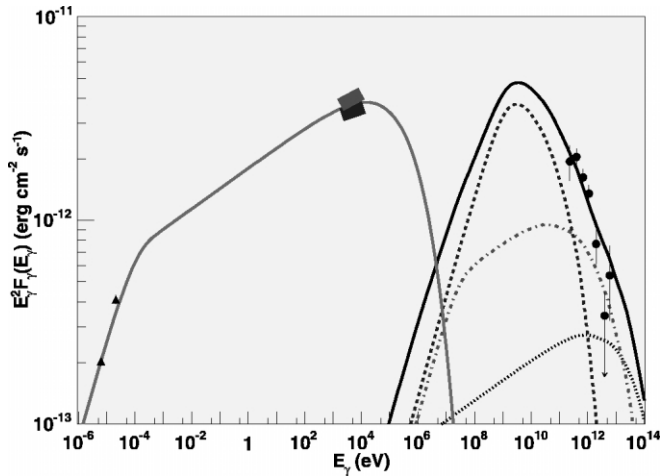


FIG. 4.—Fit to the flux spectrum of G0.9+0.1. Line styles are the same as those in Fig. 3. Radio data (VLA) from Helfand & Becker (1987); X-ray data (*BeppoSAX*) at 1.8–10 keV from Sidoli et al. (2000) (*upper solid region*) and (*XMM-Newton*) at 2–12 keV from Porquet et al. (2003) (*lower solid region*); γ -ray data (HESS) from Aharonian et al. (2005a). [See the electronic edition of the Journal for a color version of this figure.]

also that for energies higher than ~ 10 TeV, the intrinsic spectrum will be further reduced by attenuation due to pair production on the ISRF itself (Moskalenko et al. 2006).

4. DISCUSSION

We have evaluated the effect of the ISRF on the IC emission of electrons accelerated in SNRs. Our calculation shows that for an SNR located in the inner Galaxy the contribution of optical and IR photons to the IC emission exceeds the contribution of the CMB and in some cases broadens the resultant γ -ray spectrum. SNRs located close to the GC exhibit a “uni-

versal” cutoff at VHEs due to the KN effect and not due to a cutoff in the electron spectrum.

We have made a calculation of the IC and synchrotron emission for simple power-law electron spectra, including the contribution by the ISRF using the shell-type SNR RX J1713.7–3946 and composite SNR G0.9+0.1 as examples. Within the confines of a simple one-zone leptonic model, it is possible to fit the observed flux spectrum with a reasonable combination of model parameters. Observations in the GeV to sub-TeV range by the *GLAST* experiment will be critical in distinguishing between leptonic or hadronic scenarios of γ -ray production in SNRs as the predictions for the spectral shape in this energy range are distinctly different.

Finally, we point out at least two cases for the leptonic model where the contribution of the ISRF will be critical. The first will be when fitting the synchrotron peak dictates a relatively *low-energy* cutoff in the electron spectrum. In this case, the VHE γ -rays will be produced by lower energy electrons scattered off optical and IR photons. The second will be when fitting the synchrotron peak dictates a *high-energy* cutoff in the electron spectrum. An equal or exceeding contribution of optical and IR photons, but with lower energy cutoff in the spectrum of upscattered γ -rays due to the KN effect, will effectively broaden the IC peak. Observations of the TeV emission from SNRs in the inner Galaxy may thus serve as a probe of the ISRF near their location. In turn, observations of shell-type SNRs in the outer Galaxy where the CMB photons will provide the majority of the IC emission may be used to evaluate the spectrum of accelerated electrons in the shell and for studies of shock acceleration.

We thank Olaf Reimer for useful discussions. T. A. P. acknowledges partial support from the US Department of Energy. I. V. M. acknowledges partial support from NASA Astronomy and Physics Research and Analysis Program (APRA) grant.

REFERENCES

- Aharonian, F. 2002, *Nature*, 416, 797
 Aharonian, F., & Atoyan, A. M. 1999, *A&A*, 351, 330
 Aharonian, F., et al. 2005a, *A&A*, 432, L25
 ———. 2005b, *A&A*, 437, L7
 ———. 2006, *A&A*, 449, 223
 Baring, M. G., Ellison, D. C., & Slane, P. O. 2005, *Adv. Space Res.*, 35, 1041
 Bell, A. R., & Lucek, S. G. 2001, *MNRAS*, 321, 433
 Berezhko, E. G., & Völk, H. J. 2006, *A&A*, 451, 981
 Blandford, R., & Eichler, D. 1987, *Phys. Rep.*, 154, 18
 Draine, B. T., & Li, A. 2001, *ApJ*, 551, 807
 Drury, L. 1983, *Space Sci. Rev.*, 36, 57
 Ellison, D. C., & Cassam-Chenaï, G. 2005, *ApJ*, 632, 920
 Ghisellini, G., Guilbert, P. W., & Svensson, R. 1988, *ApJ*, 334, L5
 Ginzburg, V. L. 1979, *Theoretical Physics and Astrophysics* (Oxford: Pergamon)
 Girardi, L., et al. 2002, *A&A*, 391, 195
 Helfand, D. J., & Becker, R. H. 1987, *ApJ*, 314, 203
 Jones, F. C. 1968, *Phys. Rev.*, 167, 1159
 Jones, F. C., & Ellison, D. C. 1991, *Space Sci. Rev.*, 58, 259
 Juric, M., et al. 2005, *ApJ*, submitted (astro-ph/0510520)
 Koyama, K., et al. 1995, *Nature*, 378, 255
 Lazendic, J. S., et al. 2004, *ApJ*, 602, 271
 Li, A., & Draine, B. T. 2001, *ApJ*, 554, 778
 Moskalenko, I. V., Porter, T. A., & Strong, A. W. 2006, *ApJ*, 640, L155
 Moskalenko, I. V., & Strong, A. W. 2000, *ApJ*, 528, 357
 Moskalenko, I. V., Strong, A. W., Ormes, J. F., & Potgeiter, M. S. 2002, *ApJ*, 565, 280
 Ojha, D. K. 2001, *MNRAS*, 322, 426
 Pannuti, T. G., et al. 2003, *ApJ*, 593, 377
 Porquet, D., et al. 2003, *A&A*, 401, 197
 Porter, T. A., & Strong, A. W. 2006, *Proc. 29th Int. Cosmic Ray Conf.* (Pune), 77
 Sidoli, L., et al. 2000, *A&A*, 361, 719
 Strong, A. W., Moskalenko, I. V., Reimer, O., Digel, S., & Diehl, R. 2004, *A&A*, 422, L47
 Wainscoat, R. J., et al. 1992, *ApJS*, 83, 111
 Weingartner, J. C., & Draine, B. T. 2001, *ApJ*, 548, 296