



Diffuse Gamma-Rays Produced in Cosmic-Ray Interactions and the TeV-band Spectrum of RX J1713.7-3946

C.-Y. HUANG, M. POHL, S.-E. PARK AND C. D. DANIELS

Department of Physics and Astronomy, Iowa State University, Ames, IA 50011

huangc@iastate.edu

Abstract: We employ the Monte Carlo particle collision code DPMJET3.04 to determine the multiplicity spectra of various secondary particles (in addition to π^0 's) with γ 's as the final decay state, that are produced in cosmic-ray (p 's and α 's) interactions with the interstellar medium. We derive an easy-to-use γ -ray production matrix for cosmic rays with energies up to about 10 PeV. This γ -ray production matrix is applied to the GeV excess in diffuse Galactic γ -rays observed by EGRET, and we conclude the non- π^0 decay components are insufficient to explain the GeV excess, although they have contributed a different spectrum from the π^0 -decay component. We also test the hypothesis that the TeV-band γ -ray emission of the shell-type SNR RX J1713.7-3946 observed with HESS is caused by hadronic cosmic rays which are accelerated by a cosmic-ray modified shock. By the χ^2 statistics, we find a continuously softening spectrum is strongly preferred, in contrast to expectations. A hardening spectrum has about 1% probability to explain the HESS data, but then only if a hard cutoff at 50-100 TeV is imposed on the particle spectrum.

The γ -Ray Production Matrix

It is generally believed that diffuse galactic γ -rays are a good probe of the production sites and also the propagation of accelerated charged particles in the Galactic plane (see [1] and references therein). Exact knowledge of the γ -ray source spectrum resulting from hadronic interactions is of prime importance for a proper physical interpretation for the diffuse γ -rays. The production of neutral pions and their subsequent decay to γ -rays is thought to be the principal mechanism for the γ -ray hadronic component in cosmic ray interactions, and a number of parameterizations have been developed to describe γ -ray production in pp -collision [2, 3]. On the other hand, in addition to the neutral pion production, the direct γ -ray production in cosmic-ray interaction was found important [4], as was the production of (Σ^\pm , Σ^0), (K^\pm , K^0), and η particles, all of which eventually decay into γ -rays [3]. Also, the helium nuclei in cosmic rays and the interstellar medium are expected to contribute about 20-30% to the secondary production in cosmic-ray interactions, for which the multiplicity spectra may be different. In a hadronic interaction, the multi-

licity of non- π^0 secondaries with γ -rays as the final decay states is about 50% of the π^0 multiplicity. These non- π^0 secondaries in hadronic interactions might present a different γ -ray spectral profile.

This work presents a careful study of the γ -ray production in cosmic-ray (both p and α) interactions, by accounting for all decay processes including the direct production. For that purpose we employ the event generator DPMJET-III [5] to simulate secondary productions in both p-generated and He-generated interactions. We include all relevant secondary particles with γ -rays as the final decay products. For the composition of the ISM, we assume 90% protons, 10% helium nuclei, 0.02% carbon, and 0.04% oxygen. Around the energy of π^0 production threshold, where DPMJET appears unreliable, we apply a parametric model [2], that includes the resonance production for the π production. We thus derive a γ -ray production matrix for cosmic rays with energies up to about 10 PeV that can be easily used to interpret the spectra of cosmic γ -ray sources.

We consider all the decay channels and their decay fractions published by the Particle Data Group to account for all secondaries (resonances included)

calculated by DPMJET and the parametric method. The calculation shows the non- π^0 resources in hadronic interactions have contributed about 20% of the total γ -ray photons, mostly from directly produced γ -rays and decays of η , K_L^0 and K_S^0 [4]. In the cosmic-ray interactions, we calculate the γ -ray spectrum density contributed by decays of unstable secondary particles

$$\frac{Q_\gamma(E_\gamma)}{n_{ISM}} = \sum_k \int dE N_{CR}(E) c \beta \sigma(E) \frac{dn_{k,\gamma}}{dE_\gamma} \quad (1)$$

where $\frac{dn_{k,\gamma}}{dE_\gamma} = \frac{dn_{k,\gamma}}{dE_\gamma}(E_\gamma, E)$ is the γ -ray decay spectrum from secondary species k . Eq. (1) can be re-written into

$$\begin{aligned} & \frac{Q_\gamma(E_i)}{n_{ISM}} \\ &= \sum_j \Delta E_j N_{CR}(E_j) c \beta_j \sigma(E_j) \sum_k \frac{dn_{k,\gamma}}{dE_\gamma} \\ &= \sum_j \Delta E_j N_{CR}(E_j) c \beta_j \sigma_j \mathcal{M}_{ij} \end{aligned} \quad (2)$$

thus reducing this problem to a matrix operation with the γ -ray production matrix \mathcal{M}_{ij} for which, each element $\mathcal{M}_{ij} = \sum_k \frac{dn_{k,\gamma}}{dE_\gamma}$ shows the value of the resultant particle energy spectrum $\frac{dn}{dE}|_{E_\gamma=E_i, E_{CR}=E_j}$, with j being the index for the generating cosmic-ray particle (p or α) and i being the index indicating the γ -ray energy. The energy binnings E_i and E_j are defined with good resolutions [4].

We then use the γ -ray production matrix to analyze the observed spectra of diffuse Galactic emission and of the shell-type SNR RX J1713.7-3946.

The GeV Excess

With the γ -ray production matrix, we calculate the diffuse γ -ray spectrum generated by the observed cosmic-ray spectrum [7]. Fig. 1 shows the observed GeV-band γ -ray emission from the inner Galaxy [6] in comparison with the contributions from π^0 decay as well as bremsstrahlung emission describe by a power-law spectrum $\Phi_B(E)$:

$$\begin{aligned} \Phi_B(E) &\simeq 1.3 \times 10^{-8} \frac{\omega_e}{0.1 \text{ eV/cm}^3} \cdot \frac{N_{ISM}}{10^{22} \text{ cm}^{-2}} \\ &\times \left(\frac{E}{100 \text{ MeV}} \right)^{2.0-\Gamma_e} \frac{\text{erg}}{\text{cm}^2 \text{ sec sr}} \end{aligned} \quad (3)$$

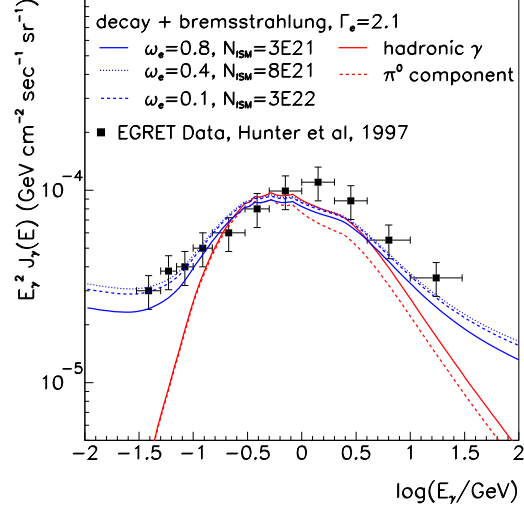


Figure 1: Diffuse γ -ray spectrum at GeV range, shown in comparison with data for the inner part of Galaxy at $315^\circ \leq l \leq 345^\circ$ and $|b| \leq 5^\circ$ [6]. See text for discussions.

with power-law spectral index $\Gamma_e = 2.1$, the electron energy density $\omega_e = 0.1, 0.4, 0.8 \text{ eV/cm}^3$, and gas column density $N_{ISM} = 3 \cdot 10^{22}, 8 \cdot 10^{21}, 3 \cdot 10^{21} \text{ cm}^{-2}$ respectively. The generating cosmic-rays are assumed with an energy density $\rho_E = 0.75 \text{ eV/cm}^3$. Models based on the locally observed cosmic-ray spectra generally predict a softer spectrum for the leptonic components, even after accounting for inverse Compton emission [6], so we may in fact overestimate the GeV-band intensity of the leptonic contribution. Nevertheless, it is clearly seen in this figure, that in the total intensity an over-shooting around $E_\gamma \simeq 300\text{-}600 \text{ MeV}$ appears in the modelled γ -ray energy distribution, whereas a deficit is present above 1 GeV. The observed spectrum of diffuse emission is always harder than the model spectrum, and we therefore conclude that an inaccurate description of hadronic γ -rays is ruled out as the origin of the GeV excess.

TeV-band Emission from RX J1713.7-3946

For the TeV-band γ -ray spectrum of the shell-type SNR J1713.7-3946 observed by the HESS collaboration [8], we use the γ -ray production matrix to test cosmic-ray acceleration models [9, 10], which predict a continuous hardening of the cosmic-ray

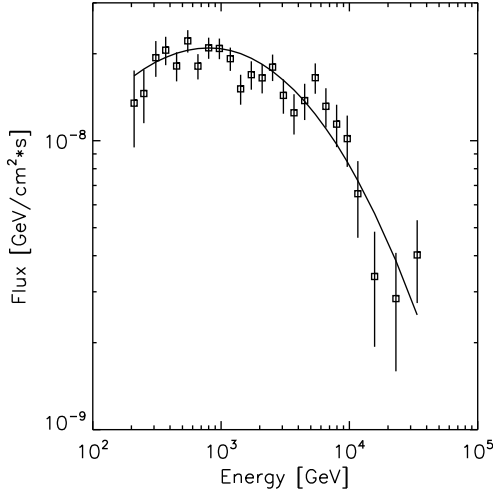


Figure 2: The TeV-band γ -ray spectrum observed from RX J1713.7-3946 with HESS [8], shown in comparison with the best-fit model of hadronic γ -ray production of Eq. (4).

spectrum up to a high-energy cutoff. We therefore parametrize the spectrum of accelerated hadrons as

$$N(E) = N_0 \left(\frac{E}{E_0} \right)^{-s + \sigma \ln \frac{E}{E_0}} \Theta [E_{\max} - E] \quad (4)$$

where Θ is the step function and $E_0 = 15$ TeV is a normalization chosen to render variations in the power-law index s statistically independent from the choice of spectral curvature, σ . The cutoff energy, E_{\max} , is a free parameter. The normalization N_0 is obtained by normalizing both the data and the model to the value at 0.97 TeV. By the χ^2 statistics, we obtain the best-fitting values and the confidence ranges of the three parameters, E_{\max} , s , and σ , given values as $s = 2.13$, $\sigma = -0.25$, and $E_{\max} \geq 200$ TeV, i.e., no cutoff. The best fit, shown in Fig. 2, involves a continuous softening and is thus not commensurate with expectations based on acceleration at a cosmic-ray modified shock [9, 10]. Note the need for data in the energy range between 1 GeV and 200 GeV that may be provided by GLAST in the near future. Fig. 3 and Fig. 4 shows the confidence ranges of the parameters in Eq. (4), for σ vs. s , σ vs. E_{\max} and s vs. E_{\max} respectively, with confidence levels of 1, 2 and 3 sigma. The contour for E_{\max} are open toward higher energies, indicating that a cut-off is not statistically required. The analysis shows that

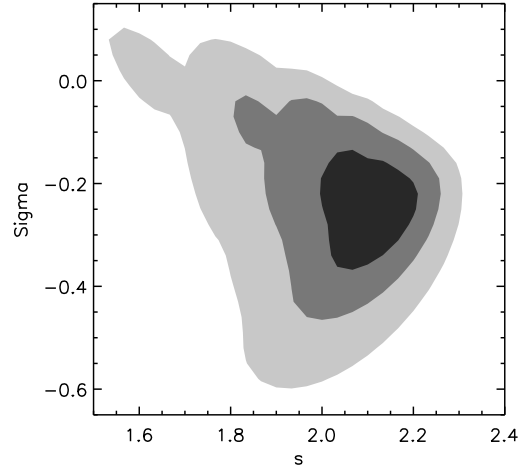


Figure 3: The confidence regions for the spectral curvature σ and the spectral index s . The shaded areas correspond to probabilities 68% (1 sigma), 95% (2 sigma) and 99.7% (3 sigma).

a very high E_{\max} is possible, but requires a negative spectral curvature, i.e., $\sigma < 0$, with confidence more than 95%, in contrast to the expectation of standard cosmic-ray modified shock models.

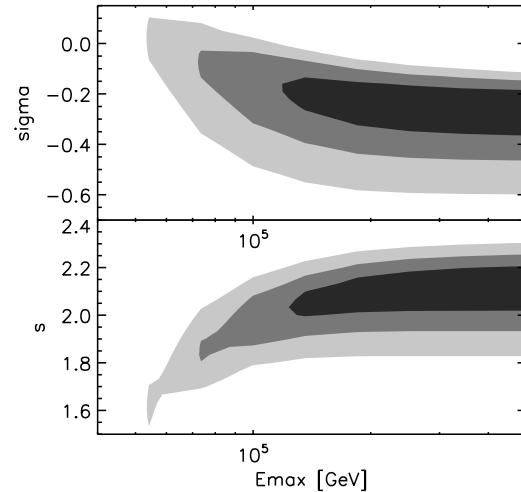


Figure 4: Confidence contours as in Fig. 3.

Note the step function term $\Theta(E_{\max} - E)$ in Eq. (4) can be replaced by an exponential term $\exp(-E/E_{\max})$. Fig. 5 shows the confidence level of E_{\max} vs. s for the new best-fit parametrization. The contour shows a minor deviation from original confidence contours in Fig. 4, however, the conclusion is not altered.

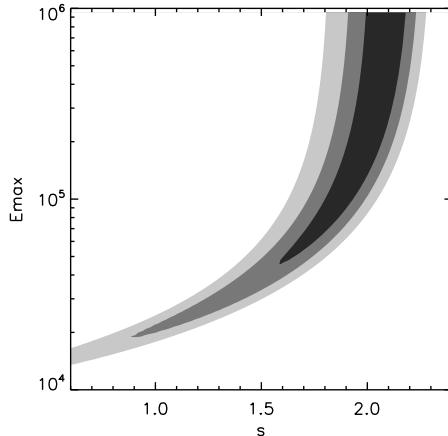


Figure 5: Confidence contour as in Fig. 3 but for an exponential term $\exp(-E/E_{\max})$ in Eq. (4) instead of the step function.

Conclusions

We have considered a full picture of the hadronic γ -rays in cosmic-ray interactions and introduced an easy-to-use γ -ray production matrix which can be used for arbitrary cosmic-ray spectrum. The matrices are available for download at website <http://cherenkov.physics.iastate.edu/gamma-prod>. We apply the production matrix to calculate the γ -ray GeV excess and also the TeV-band spectrum of SNR RX J1713.7-3946. We conclude that 1) the modifications in the GeV-band γ -ray emission of hadronic origin are insufficient to explain the GeV excess in diffuse galactic γ -rays; 2) a soft cut-off at about 100 TeV is statistically required in the particle spectrum if the TeV-band spectrum of RX J1713.7-3946 as observed with HESS is caused by cosmic-ray nucleons; 3) no evidence for efficient nucleon acceleration to energies near the knee in the cosmic-ray spectrum, nor evidence of the spectral curvature and hardness predicted by standard models of cosmic-ray modified shock acceleration. We emphasize the need for GLAST data to better constrain the γ -ray spectrum below 100 GeV.

In addition to γ -ray production matrix, we have also produced the production matrices of all particles that are stable on a time scale relevant for cosmic-ray propagation. The leptonic production by the same approach will be discussed in an independent article.

Acknowledgments

Grant support from NASA with award No. NAG5-13559 is gratefully acknowledged.

References

- [1] A.D. Erlykin, M. Lipski, and A.W. Wolfendale. High energy cosmic ray spectroscopy. IV. The evidence from direct observations at lower energies and directional anisotropies. *Astropart. Phys.*, 8:283–292, 1998.
- [2] T. Kamae et al. Parameterization of γ , e^\pm and Neutrino Spectra Produced by p-p Interaction in Astronomical Environments. *APJ*, 647:692–708, 2006.
- [3] S. R. Kelner, F. A. Aharonian, and V. V. Bugayov. Energy spectra of gamma rays, electrons, and neutrinos produced at proton-proton interactions in the very high energy regime. *PRD*, 74:034018–034033, 2006.
- [4] C.-Y. Huang, S.-E. Park, M. Pohl, and C.D. Daniels. Gamma-rays produced in cosmic-ray interactions and the TeV-band spectrum of RX J1713.7-3946. *Astropart. Phys.*, 27:429–439, 2007.
- [5] S. Roesler, R. Engel, and J. Ranft. Advanced Monte Carlo for Radiation Physics. In *Particle Transport Simulation and Applications (MC 2000)*, 2000.
- [6] S. D. Hunter et al. EGRET Observations of the Diffuse Gamma-Ray Emission from the Galactic Plane. *APJ*, 481:205–240, 1997.
- [7] M. Mori. The Galactic Diffuse Gamma-Ray Spectrum from Cosmic-Ray Proton Interactions. *APJ*, 478:225–232, 1997.
- [8] F. A. Aharonian et al. The HESS Collaboration. A detailed spectral and morphological study of the gamma-ray supernova remnant RX J1713.7-3946 with HESS. *AA*, 449:223–242, 2006.
- [9] E. Amato and P. Blasi. Non-linear particle acceleration at non-relativistic shock waves in the presence of self-generated turbulence. *MNRAS*, 371:1251–1258, 2006.
- [10] E. G. Berezhko and D. C. Ellison. A Simple Model of Nonlinear Diffusive Shock Acceleration. *APJ*, 526:385–399, 1999.