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

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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.

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γ-ray production matrix in hadronic Interactions

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 [1] 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 [3].

In the cosmic-ray interactions, we calculate the γ-ray spectrum contributed by decays of unstable secondary particles

$$Q_\gamma(E_\gamma) = \sum_k n_{ISM} \int_{E_{CR}} dE_{CR}\; N_{CR}(E_{CR})\, c\beta_{CR}\, \sigma(E_{CR})\, \frac{dn_{k,\gamma}}{dE_\gamma}(E_\gamma, E_{CR}) \tag{1}$$

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

$$Q_\gamma(E_i) = \sum_j n_{ISM}\, \Delta E_j\; N_{CR}(E_j)\, c\beta_j\, \sigma(E_j) \sum_k \frac{dn_{k,\gamma}}{dE_\gamma}(E_i, E_j) = \sum_j n_{ISM}\, \Delta E_j\, N_{CR}(E_j)\, c\beta_j\, \sigma_j\, \mathbb{M}_{ij} \tag{2}$$

thus reducing this problem to a matrix operation with the γ-ray production matrix $\mathbb{M}_{ij}$ for which, each element $\mathbb{M}_{ij}$ 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 [3].

We 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. We find that the GeV excess is probably not the result of an inappropriate model of hadronic γ-ray production. We also test the hypothesis that the TeV-band γ-ray emission of SNR RX J1713.7-3946 observed with

HESS is caused by hadronic cosmic rays that have a spectrum according to current theories of cosmic-ray modified shock acceleration.

Application: the GeV-band γ-ray spectrum and the TeV-band spectrum of RX J1713.7-3946

With the γ-ray production matrix, we calculate the diffuse γ-ray spectrum generated by the observed cosmic-ray spectrum [4]. Fig. 1 (Left) shows the observed GeV-band γ-ray emission from the inner Galaxy [5] in comparison with the contributions from π^0 decay as well as bremsstrahlung emission describe by a power-law spectrum $\Phi_{\rm B}(E)$:

$$\Phi_{\rm B}(E) \simeq 1.3\times 10^{-8}\frac{\omega_e}{0.1\ \mathrm{eV/cm^3}}\cdot\frac{N_{ISM}}{10^{22}\ \mathrm{cm^{-2}}}\cdot\left(\frac{E}{100\ \mathrm{MeV}}\right)^{2.0-\Gamma_e}\quad\frac{\mathrm{erg}}{\mathrm{cm^2\ sec\ sr}} \tag{3}$$

with power-law spectral index $\Gamma_e = 2.1$, the electron energy density $\omega_e = 0.1,\ 0.4,\ 0.8\ \mathrm{eV/cm^3}$, and the gas column density $N_{ISM} = 3\ \times 10^{22},\ 8\ \times 10^{21},\ 3\ \times 10^{21}\mathrm{cm^{-2}}$, respectively. The generating cosmic-rays are assumed with an energy density $\rho_E = 0.75\ \mathrm{eV/cm^3}$. 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 [5], 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 $E_\gamma \simeq$ 300-600 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.

For the TeV-band γ-ray spectrum of the shell-type SNR J1713.7-3946 observed by the HESS collaboration [6], we use the γ-ray production matrix to test cosmic-ray acceleration models [7, 8], which predict a continuous hardening of the cosmic-ray spectrum up to a high-energy cutoff. We therefore parametrize the spectrum of accelerated hadrons as

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

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, $E_{\rm max}$, 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, $E_{\rm max}$, s, and σ, given values as $s = 2.13$, $\sigma = -0.25$, and $E_{\rm max} \gtrsim 200$ TeV, i.e. no cutoff. The best fit, shown in Fig. 1 (Right), involves a continuous softening and is thus not commensurate with expectations based on acceleration at a cosmic-ray modified shock [7, 8]. Noted that very valuable would be data in the energy range between 1 GeV and 200 GeV that may be provided by GLAST in the near future. Fig. 2 shows the confidence ranges of the parameters in Eq. (4), with confidence levels of 1, 2 and 3 sigma. The analysis strongly suggests a negative spectral curvature, $\sigma < 0$, with confidence more than 95%, in contrast to the expectation of standard cosmic-ray modified shock models.

Conclusion

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.

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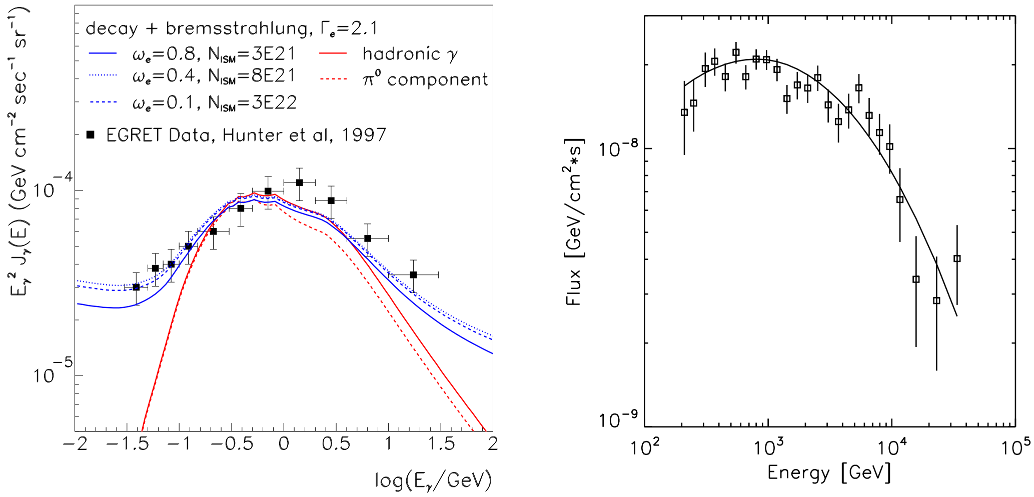

FIGURE 1. Left: Diffuse γ-ray spectrum at GeV range, shown in comparison with data for the inner part of Galaxy at $315^0 \leq l \leq 345^0$ and $|b| \leq 5^0$ [5]. See text for discussions. Right: The TeV-band γ-ray spectrum observed from RX J1713.7-3946 with HESS [6], shown in comparison with the best-fit model of hadronic γ-ray production of Eq. (4).

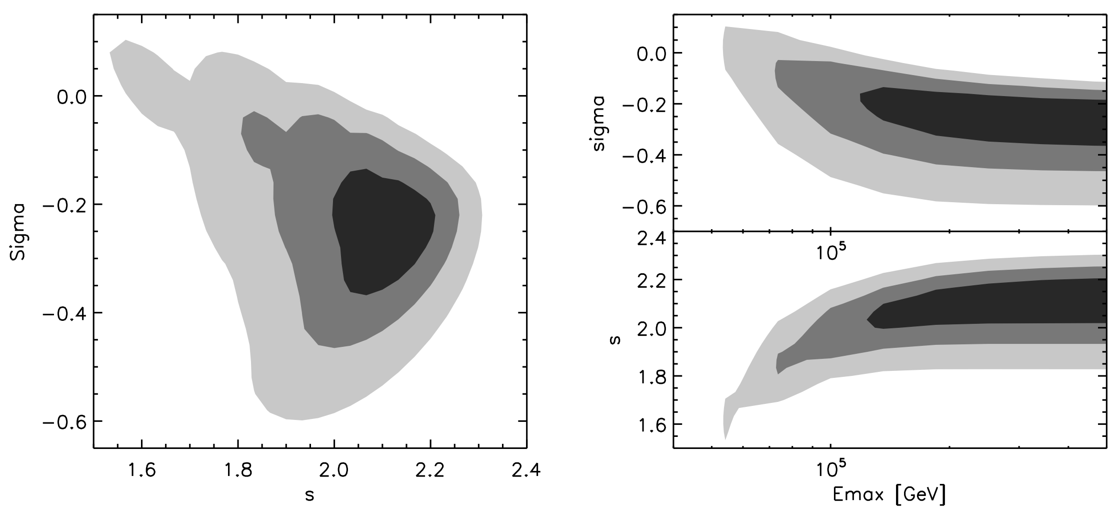

FIGURE 2. Left: The confidence regions for the spectral curvature σ and the spectral index s. The shaded areas correspond to probabilities 68% (1 sigma), 95% (2 sigma) and 99.7% (3 sigma). Right: The confidence regions for the spectral curvature σ and the spectral index s, versus the cutoff energy $E_{\max}$. The contour levels are arranged as the same.

REFERENCES

1. S. Roesler, R. Engel and J. Ranft, Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications (MC 2000), Lisbon, 2000
2. T. Kamae, N. Karlsson, M. Tsunefumi, A. Toshinori, K. Tatsumi, Astrophys. J. 647 (2006) 692.
3. C.-Y. Huang, S.-E. Park, M. Pohl and C. D. Daniels, 2007 Astropart. Phys in press
4. M. Mori, Astrophys. J. 478 (1997) 225.
5. S. D. Hunter et al., Astrophys. J. 481 (1997) 205.
6. The HESS Collaboration, F. A. Aharonian et al., Astron. Astrophys. 449 (2006) 223.
7. E. G. Berezhko and D. C. Ellison, Astrophys. J. 526 (1999) 385.
8. E. Amato and P. Blasi, Mon. Not. R. Astron. Soc. 371 (2006) 1251.