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Hadronic Interpretation of High-Energy Gamma-Rays from Two TeV Sources Coincident with Molecular Clouds Overtaken by Supernova Remnants *

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We present a possible hadronic explanation of the high-energy γ-ray emission from two very high-energy (VHE) sources, HESS J1745–303 (A) and HESS J1714–385, which coincide with supernova remnants (SNRs) interacting with dense molecular clouds (MCs). We calculate the proton spectra and the corresponding hadronic γ-ray spectra for different Mach numbers of the shock wave in a semi-analytical model for the non-linear shock acceleration process, then apply the model to the two newly discovered TeV sources. The results show that the γ-ray spectra for the two sources with energies above 100 MeV detected by HESS and EGRET can be reproduced with low Mach numbers about 2.5. Thus the high-energy γ-ray origin for each one of the two sources can be interpreted as proton–proton (p–p) collisions in MCs overtaken by an SNR shock wave.

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Recently, two sources, HESS J1745–303 (A) and HESS J1714–385, have been detected to emit TeV γ-rays by HESS.[1,2] These two TeV γ-ray sources have following properties: (1) they are coincident with SNR shocks interacting with MCs and the observations of the CO ($J = 1 \rightarrow 0$) transition and OH masers at 1720 MHz strongly suggest that MCs around the remnants are overtaken by the SNR shock fronts;[1,2] (2) strong magnetic fields ($\sim$ mG) are indicated from Zeeman splitting measurements for the two TeV sources,[3,4] which strongly favours a hadronic origin of the TeV γ-rays; and (3) the two TeV γ-ray sources likely associate with the EGRET sources, 3EG J1744–3011 and 3EG J1714–3857, respectively. Importantly, p–p interactions as the accelerated protons collide with the ambient matter can be greatly enhanced when the SNR shock propagates into the dense MCs. Therefore, it is very likely that the high-energy γ-rays with energies above $\sim$ 100 MeV from the three sources are produced mainly via hadronic processes. However, with the assumption that HESS J1745–303 (A) and HESS J1714–385 associate with the EGRET sources 3EG J1744–3011 and 3EG J1714–3857, respectively, the hadronic spectrum ($E > 100$ MeV) with the usual proton index ~ 2 for each source can not be well consistent with the HESS and EGRET observations.

It has been proposed that the back-reaction of the protons accelerated at shocks can be significant and the system is intrinsically non-linear due to the back-reaction of the accelerated particles on the structure of the shock,[5,6] resulting in non-linear cosmic ray (CR) acceleration models which have been studied extensively both numerically[7,8] and semi-analytically.[5,6] The accelerated particles in such models have a harder spectrum compared to in the test particle regime in which the back-reaction effects are neglected.

In this Letter, we investigate the high-energy hadronic emission from the accelerated protons in a shock propagating in dense MCs by using the one-dimensional semi-analytical model of non-linear particle acceleration given by Blasi.[9] Our results show that the HESS and EGRET observations of the VHE sources, HESS J1745–303 (A) and HESS J1714–385, can be explained with low Mach numbers ~ 2.5 within this scenario.

The pitch-angle averaged steady-state distribution of particles accelerated at a shock in one dimension satisfies the diffusive transport equation,[5,6,9]

$$\frac{\partial}{\partial x}\left[D\frac{\partial}{\partial x}f(x,p)\right] - u\frac{\partial f(x,p)}{\partial x} + \frac{1}{3}\frac{du}{dx}p\frac{\partial f(x,p)}{\partial p} + Q(x,p) = 0, \quad (1)$$

where the coordinate x is directed along the shock normal from downstream to upstream, D is the diffusion coefficient and u is the fluid velocity in the shock frame, which equals u_2 downstream ($x < 0$) and changes continuously upstream, from u_1 immediately upstream ($x = 0^+$) of the subshock to u_0 at upstream infinity ($x = +\infty$). Here we just consider the case of proton acceleration. With the assumption that the particles are injected at immediate upstream of the subshock, the source function can be written as $Q(x,p) = Q_0(p)\delta(x)$. For monoenergetic injection, $Q_0(p)$ is

$$Q_0(p) = \frac{\eta n_{\mathrm{gas},1} u_1}{4\pi p_{\mathrm{inj}}^2}\delta(p - p_{\mathrm{inj}}), \quad (2)$$

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where $p_{\rm inj}$ is the injection momentum, $n_{\rm gas,1}$ is the gas density at $x = 0^+$ and η is the fraction of particles injected in the acceleration process. With the injection recipe known as thermal leakage, η can be described as $\eta = 4(R_{\rm sub}-1)\xi^3 e^{-\xi^2}/3\pi^{1/2}$,[5,10] where $R_{\rm sub} = u_1/u_2$ is the compression factor at the subshock and ξ is a parameter of the order of 2–4 describing the injection momentum of the thermal particles in the downstream region ($p_{\rm inj} = \xi p_{\rm th,2}$). We use $\xi = 3.5$ as in Ref. [5], $p_{\rm th,2} = (2mk_BT_2)^{1/2}$ is the thermal peak momentum of the particles in the downstream fluid with temperature T_2, m is the mass of the accelerated particles and k_B is the Boltzmann constant. Assuming that the heating of the gas upstream is adiabatic, with the conservation condition of momentum fluxes between the two sides of the subshock, we can derive the relation between the temperature of the gas far upstream T_0 and T_2, i.e., $T_2 = (\gamma_g M_0^2/R_{\rm tot})[R_{\rm sub}/R_{\rm tot} - 1/R_{\rm tot} + (1/\gamma_g M_0^2)(R_{\rm tot}/R_{\rm sub})^{\gamma_g}]T_0$, where M_0 is the fluid Mach number far upstream, $R_{\rm tot} = u_0/u_2$ is the total compression factor, γ_g is the ratio of specific heats ($\gamma_g = 5/3$ for an ideal gas). We use $T_0 = 10^6$ K in this paper, corresponding to a sound speed of $\sim 117\,{\rm km\,s^{-1}}$.

With the assumption that the diffusion is p dependent and that therefore particles with larger momenta move farther away from the shock than those with lower momenta, only particles with momentum $\geq p$ can reach the point x_p and thus the pressure of the accelerated particles at the point can be described as

$$P_{{\rm CR},p} = \frac{4\pi}{3}\int_p^{p_{\rm max}} dp' p'^3 v(p') f_0(p'), \qquad (3)$$

where $v(p)$ is the velocity of particles with momentum p. Furthermore, the particle distribution function $f_0(p)$ at the shock can be implicitly written as

$$f_0(p) = \left[\frac{3R_{\rm tot}}{R_{\rm tot}U(p)-1}\right]\frac{\eta n_{\rm gas,0}}{4\pi p_{\rm inj}^3} \times \exp\left[-\int_{p_{\rm inj}}^{p_{\rm max}}\frac{dp'}{p'}\frac{3R_{\rm tot}U(p')}{R_{\rm tot}U(p')-1}\right], \qquad (4)$$

where $n_{\rm gas,0}$ is the gas density far upstream ($x = +\infty$), $p_{\rm max}$ is the maximum momentum of the accelerated particles. We use $p_{\rm max} = 1.0\times10^5$ mc in this paper, which is a typical value for an SNR with ambient magnetic strength 0.5 mG. $U(p)$ can be solved using an equation deduced from the conservation of the mass and momentum fluxes with the boundary condition $U(p_{\rm inj}) = R_{\rm sub}/R_{\rm tot}$ and $U(p_{\rm max}) = 1$, and then a value of $R_{\rm sub}$ can be achieved by an iterative procedure to satisfy the boundary conditions.[9]

The resulting particle spectra and slopes for different Mach numbers, $M_0 = 2.5$ (solid line), $M_0 = 3.0$ (dashed line), $M_0 = 5.0$ (dotted line), and $M_0 = 10.0$ (dash-dotted line), are shown in Figs. 1(a) and 1(b). The concave shape of the particle distribution is obvious for a high Mach number and the spectrum is flatter at high momenta; however, for a low Mach number ($M_0 = 2.5$ in Fig. 1), the p dependent slope has little difference in the band from $p_{\rm inj}$ to $p_{\rm max}$ and the corresponding particle distribution is power-law like.

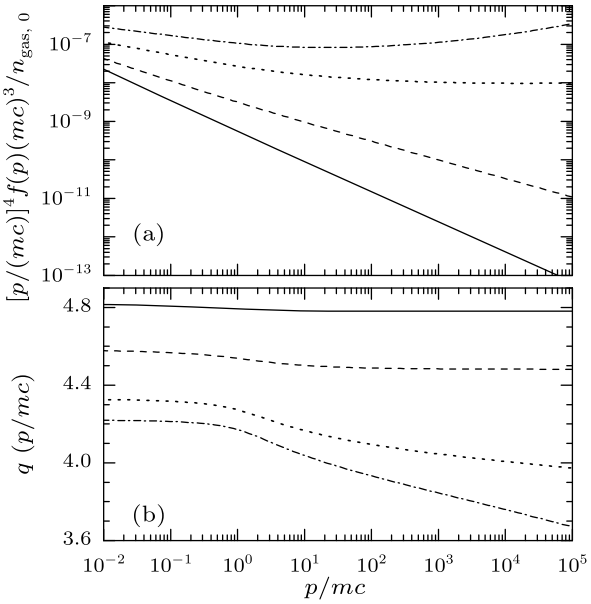


Fig. 1. (a) Spectra of accelerated particles at the shock for different Mach numbers, $M_0 = 2.5$ (solid line), $M_0 = 3.0$ (dashed line), $M_0 = 5.0$ (dotted line), and $M_0 = 10.0$ (dash-dotted line). (b) The local slope with the same parameters for the same values of Mach number.

High-energy γ-rays can be produced via hadronic interactions as relativistic protons collide with the ambient matter. Assuming the accelerated protons distribute homogeneously and most of the emission is from downstream of the shock, and using the distribution function at the shock to represent the particle distribution in the whole emitting zone, the volume-averaged emissivity for photons produced in p-p interactions can be written as

$$Q(E) = 4\pi\mu_{pp} n_H \int dE_p J_p(E_p)\frac{d\sigma(E,E_p)}{dE}, \qquad (5)$$

where E_p is the proton kinetic energy, n_H is the ambient proton number density, $\mu_{pp} = 1.45$ is an enhancement factor for collisions involving heavy nuclei,[11] and $J_p(E_p) = vp^2 f_0(p)dp/dE_p$ is the volume-average proton density and v is the particles' velocity. We use the differential cross-section for photons $d\sigma(E,E_{\rm p})/dE$ presented in[12] to calculate the hadronic γ-rays produced in p-p collisions. Finally, the photon flux observed at the earth can be obtained with

$$F(E) = \frac{VQ(E)}{4\pi d^2}, \qquad (6)$$

where d is the distance from the earth to the source

and V is the average emitting volume of the source. Note that bremsstrahlung and inverse Compton scattering of secondary $e^{\pm}$ pairs produced in p-p collisions can contribute to the γ-ray emission from an SNR; however, the contribution is usually orders of magnitude smaller than that directly from π^0 decay,[13] thus we neglect the emission from the secondary $e^{\pm}$ pairs in this study.

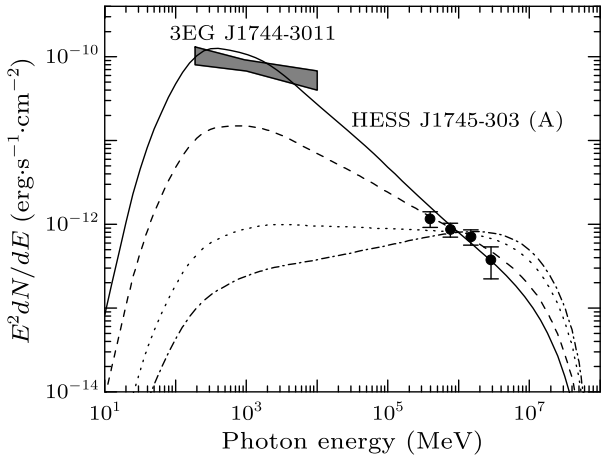


Fig. 2. Resulting spectral energy distribution of γ-rays from the region A of HESS J1745–303 with $d = 7.6$ kpc for $M_0 = 2.5$, $n_{H,up} = 319/h_{pc}\,\mathrm{cm}^{-3}$ (solid line); $M_0 = 3$, $n_{H,up} = 36/h_{pc}\,\mathrm{cm}^{-3}$ (dashed line); $M_0 = 5$, $n_{H,up} = 2.0/h_{pc}\,\mathrm{cm}^{-3}$ (dotted line); and $M_0 = 10$, $n_{H,up} = 0.4/h_{pc}\,\mathrm{cm}^{-3}$ (dash-dotted line) with the EGRET[18] and HESS[1] observations.

HESS J1745–303 is an extended TeV source discovered in the HESS survey of the inner Galaxy in the VHE γ-ray band.[14] Recently, Aharonian *et al.*[1] reported the latest HESS results on the VHE source, and the spectrum can be well fitted by a power law with photon index ~ 2.71. The VHE emission has a complicated morphology with three peaks A, B, C, and the possible candidates of the source have been investigated with the recent XMM-Newton observations and a variety of source catalogs and lower-energy survey data. The results show that no single counterpart can account for the TeV emission; however, the region A with a photon index of ~ 2.67 and an integration radius of 0.14°, corresponding to 18.6 pc at $d = 7.6$ kpc, may be associated with the shell of the SNR G359.1–0.5.[1] Dense matter around the shell has been indicated from the ^{12}CO emission line ($J = 1 \rightarrow 0$)[15] and the detected OH masers near the edge of the shell suggest that the dense matter are shocked by the SNR shell.[16] Then the VHE γ-rays from HESS J1745–303 are very likely from the shocked MCs.

G359.1–0.5 is a middle aged SNR ($\geq 10^4$ yr) with a distance of ~ 7.6 kpc, and a non-thermal shell appears apparently in the radio band.[15] Aharonian *et al.*[1] show that a cloud component is partially coincident with HESS J1745–303 and the H_2 mass in the cloud is about 5×10^4 $M_\odot$ with a density of $\sim 5 \times 10^3\,\mathrm{cm}^{-3}$. The ASCA observations of the remnant showed no evidence for a shell in the band 3.2–1000 keV, and only thermal diffuse emission appeared in the central region.[17] The unidentified EGRET source 3EG J1744–3011 has an integral flux of $(63.0 \pm 7.1) \times 10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with a photon index of 2.17 ± 0.08, and encloses most part of HESS J1745–303.[1,18]

Assuming the EGRET source 3EG J1744–3011 associates with HESS J1745–303 (A), we use the model in this section to investigate the high-energy γ-ray emission from it. The resulting spectra for different Mach numbers are shown in Fig. 2 with parameters $d = 7.6$ kpc and emitting volume $\pi 18.6^2 \times h_{pc}\,\mathrm{pc}^3$, where h_{pc} is the average thickness of the emitting region in units of pc. The proton number density $n_{H,up}$ is chosen for each Mach number to make the result match the HESS observations. With a low Mach number 2.5 and $n_{H,up} = 319/h_{pc}\,\mathrm{cm}^{-3}$, the slope of the proton spectrum has little change in the whole band, and the HESS and EGRET observations on this source can be well reproduced.

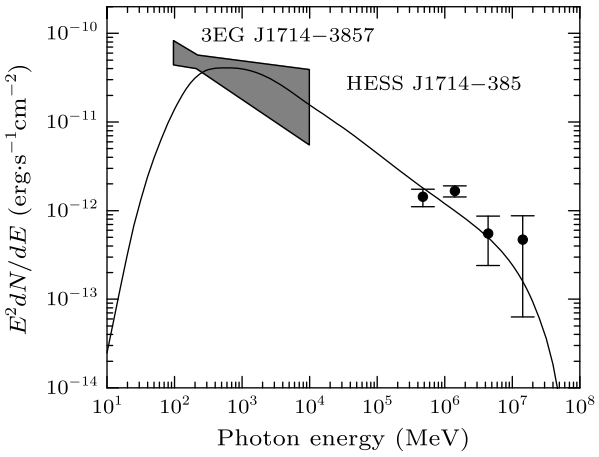


Fig. 3. Resulting spectral energy distribution of γ-rays from HESS J1714–385 with $d = 11.0$ kpc for $M_0 = 2.8$, $n_{H,up} = 174/h_{pc}\,\mathrm{cm}^{-3}$ with the EGRET[18] and HESS[2] observations.

The SNR complex CTB containing three SNRs has been detected with HESS and a VHE γ-ray source HESS J1714–385, which is extended with a size of $4' \pm 1'$ and can be described by a power-law with an index of 2.30 ± 0.13 and a differential flux at 1 TeV of $8.7 \pm 1.0_{\mathrm{stat}} \pm 1.8_{\mathrm{sys}} \times 10^{-13}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\ \mathrm{TeV}^{-1}$, coincident with the SNR CTB 37A (G348.5+0.1) was discovered.[2] The SNR has a distance of 10.3 ± 3.5 kpc deduced from the hydrogen absorption.[19] Reynoso and Mangum[2] reported the survey in the CO ($J = 1 \rightarrow 0$) transition on the SNR and several MCs with H_2 densities ranging between $150\,\mathrm{cm}^{-3}$ and $660\,\mathrm{cm}^{-3}$ have been found towards CTB 37A. Moreover, several OH masers have been detected towards the SNR[21]

and the velocities of the masers are consistent with those of the three MCs observed in CO ($1 \rightarrow 0$) transition.[2,20] The velocities of the masers and their superposition with the MCs strongly indicate that the MCs are being overtaken by the shock wave of the SNR G348.5+0.1.[2,20]

Furthermore, HESS J1714–385 is located within the 95% confidence contour of the unidentified EGRET source 3EG J1714–3857, which has a spectral index of 2.3 ± 0.2, and an agreement of the index in the global fit from EGRET to HESS observations with those for the two individual sources makes HESS J1714–385 a counterpart candidate for 3EG J1714–3857.[2,18] Fig. 3 shows the comparison of the resulting spectrum with the EGEET and HESS observations. The parameters are $d = 11.0\,\mathrm{kpc}$, $M_0 = 2.8$ and emitting volume $\pi 12.8^2 \times h_{pc}\,\mathrm{pc}^3$. Similarly, $n_{H,up}$ must be $1422/h_{pc}\,\mathrm{cm}^{-3}$ to make the result consistent with the HESS observations in TeV band and the EGERT observations can be reproduced with those parameters.

Based on the semi-analytical approach to particle distribution at a shock in[9], we study the hadronic γ-ray emission from two newly discovered VHE sources in which interactions between SNRs and MCs seem to exist from the observations of CO emission and OH masers. The high-energy γ-ray emission ($E > 100\,\mathrm{MeV}$) from the two sources, HESS J1745–303 (region A) and HESS J1714–385, which may be associated with 3EG J1744–3011 and 3EG J1714–3857, respectively, can be explained with low Mach numbers ~ 2.5 in the model. In such a case, the high-energy γ-rays from the two sources are produced via hadronic p-p interactions when the SNR shock waves propagate in dense MCs.

The region B/C of HESS J1745–303 can also relate to 3EG J1744–3011. Especially, Torres *et al.*[22] argued that 3EG J1744–3011 is variable on year timescales based on the study of the long-term variability of EGRET sources. If the variability is true, 3EG J1744–3011 may not be the counterpart of HESS J1745–303.[1] Furthermore, the unidentified EGRET source 3EG J1714- 3857 overlaps the northern part of the young SNR RX J1713.7–3946, and RX J1713.7–3946 and HESS J1713–381 may also contribute to the MeV/GeV emission of 3EG J1714–3857.[2] Therefore, the associations of the three TeV sources with their EGERT counterparts are not absolutely confirmed, and the coming γ-ray observations with the Fermi Gamma-ray Space Telescope are essential to detect the MeV/GeV candidates of the VHE sources coincident with interactions between SNR with dense MCs in MeV/GeV γ-rays, and to understand the spectral properties in the high-energy γ-ray band, and then the emission processes in the systems can be investigated more definitely.

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