

ON THE GAMMA-RAY SPECTRA RADIATED BY PROTONS ACCELERATED IN SUPERNOVA REMNANT SHOCKS NEAR MOLECULAR CLOUDS: THE CASE OF SUPERNOVA REMNANT RX J1713.7–3946

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Received 2004 August 16; accepted 2005 March 18; published 2005 April 5

ABSTRACT

Cosmic rays (CRs) are thought to be accelerated in supernova remnants (SNRs). The most favorable situation for proving that the main, hadronic CR component is accelerated there is when CRs interact with dense gases, such as molecular clouds (MCs) that surround the SN shock. Here, a new mechanism of spectrum formation in partially ionized gases near SNRs is proposed. Using an analytic model of nonlinear diffusive shock acceleration, we calculate the spectra of protons and estimate the resulting γ -ray emission occurring when the SNR shock approaches an MC. We show that the spectrum develops a break in the TeV range and that its GeV component is suppressed. These modifications to the standard theory occur because of the proximity of the partially ionized MC gas and because of the physics of particle and Alfvén wave propagation inside the gas. Possible applications of the new spectra to the recent CANGAROO and HESS observations of the SNR RX J1713.7–3946 are discussed.

Subject headings: acceleration of particles — cosmic rays — shock waves — supernova remnants — turbulence

1. INTRODUCTION

Cosmic rays (CRs) travel to us through the chaotic magnetic field of the Galaxy. Therefore, the only way to connect them to their accelerator is through the on-site radiation. Accelerated electrons have already been detected in supernova remnant (SNR) shocks (Koyama et al. 1995). However, electrons comprise only 1%–2% of the CR intensity above 4–5 GeV. Therefore, distinguishing between a leptonic and a hadronic origin of the observed TeV emission from SNRs is a key to the proof of the supernova origin of CRs. Simultaneous monitoring of X-ray and γ -ray energy bands is an indispensable tool for that purpose. The same TeV *electrons* radiate in X- and γ -rays via synchrotron and inverse Compton mechanisms, respectively (e.g., Sturmer et al. 1997; Reynolds 1998). Accelerated *protons* can be detected *only* near their own (most interestingly TeV) energy band through their interaction with an ambient gas. Therefore, the “smoking gun” for *proton acceleration* should be the γ -ray emission, without an X-ray emission that can be identified as the electron synchrotron radiation. Molecular clouds (MCs) adjacent to the SNR will dramatically enhance proton visibility (e.g., Aharonian et al. 1994; Drury et al. 1994).

However, to conclusively detect the acceleration of super-TeV nuclei turned out to be a very difficult task. Despite extensive search campaigns (e.g., Buckley et al. 1998; Völk 2000), only three SNRs have shown detectable TeV emission so far (Tanimori et al. 1998; Muraishi et al. 2000; Aharonian et al. 2001; Enomoto et al. 2002). Nevertheless, a signature of protons accelerated to super-TeV energies was reportedly discovered in the SNR RX J1713.7–3946 by the CANGAROO team (Enomoto et al. 2002). Recently, this remnant has been confirmed as a TeV source, with significantly reduced systematic and statistical errors in the range 1–10 TeV, by the HESS collaboration (Aharonian et al. 2004). This remnant is of a shell type, typical for the major acceleration models, and rather abun-

dant in the Galaxy. Therefore, after some verification of the data and analysis, it could serve as direct evidence of the CR-SNR connection.

A number of groups (e.g., Butt et al. 2002; Reimer & Pohl 2002) reanalyzed the data of Enomoto et al. (2002) and claimed that the nucleonic interpretation is “highly unlikely” because of an alleged inconsistency with the commonly assumed first-order Fermi acceleration theory. We argue below that if (as it is assumed for this SNR by Butt et al. 2001 and Enomoto et al. 2002) some of the accelerated particles begin to interact with a partially ionized dense gas such as an MC in the *north-western* rim of the remnant, the standard acceleration model is not applicable. In particular, the nonlinearity of the acceleration process as well as the Alfvén wave evanescence in the MC are essential. Therefore, the analyses by both sides of the controversy are oversimplified, and we believe that a conclusive case for or against a nucleonic origin of the emission has not been made. Moreover, a recent analysis by Pannuti et al. (2003) indicates that the standard acceleration model applied to TeV electrons does not adequately fit the TeV data either, unless the X-ray-emitting filaments have an unreasonably low filling factor of 10^{-3} . Lazendic et al. (2004) have increased it to 10^{-2} by allowing a smoother spectrum cutoff.

These analyses indicate that modifications to the accelerated particle spectra are required. Namely, a low-energy cutoff above 100 GeV and/or a *spectral break* would support the nucleonic scenario (Reimer & Pohl 2002) while models with an exponential cutoff rather than a break provide only a bad fit. Such modifications are suggested below.

The controversy about the TeV observations of the SNR RX J1713.7–3946 is fundamental and will clearly impair our understanding of future observations of SNRs nearby MCs. Therefore, in this Letter we revisit shock acceleration theory and include the following physical phenomena in the model: (1) the nonlinearity of the acceleration process, i.e., the modification of the flow by accelerated particles; (2) a position-dependent *low-energy cutoff* of accelerated particles ahead of the shock, which is *well known* to be present in analytic so-

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lutions for the shock acceleration problem;³ and (3) impairment of CR confinement in a dense gas (MC) due to nonpropagation of some Alfvén waves. The latter phenomenon produces a break (curvature) in the particle and radiation spectra in the TeV energy range and, in combination with the first phenomenon, results in a spectral slope significantly different from the usual predictions of linear theory supplemented with the high-energy cutoff, which was used in the analyses of Enomoto et al. (2002) and Reimer & Pohl (2002), for example.

2. LOW-ENERGY CUTOFF AND THE ABSENCE OF THERMAL X-RAY EMISSION

The diffusive shock acceleration (DSA) mechanism operates by scattering charged particles off magnetic irregularities (Alfvén waves) across a shock, such as a SN blast wave (e.g., Blandford & Eichler 1987). In the linear acceleration regime, the momentum distribution is a power law, $p^2 f_0(p) = C p^{-s}$, where C is a normalization constant and the index $s = (r + 2)/(r - 1)$ depends only on the shock compression ratio r . As soon as the flow is disturbed by the pressure of accelerated particles, the spectrum becomes more complex. It flattens toward higher energies and may become steeper at lower energies. The spectrum $f_0(p)$ is the *downstream* spectrum, which is coordinate-independent in both the linear and nonlinear regimes. Here the upstream spectrum is more important since the interaction with the adjacent MCs starts *upstream* where a low-energy *cutoff* occurs. Indeed, the solution upstream, valid for both the linear and nonlinear regimes, reads (e.g., Malkov & Drury 2001)

$$f(p, x) = f_0(p) \exp\left(-\frac{\alpha}{\kappa} \int_0^x u dx\right). \quad (1)$$

Here $f_0(p)$ is the spectrum downstream, $\alpha(p) \sim 1$. The x -coordinate points upstream ($x > 0$) from the shock ($x = 0$), and $u(x) > 0$ is the speed of the plasma flowing into the shock [$u(x) \sim V_{\text{shock}}$]. Now, $\kappa(p)$ grows with p , most likely linearly; $\kappa \approx \kappa' p$. According to equation (1), there exists a CR precursor, which is of the length $l_{\text{CR}} = \kappa(p_{\text{max}})/V_{\text{shock}}$. Furthermore, high-energy particles diffuse ahead of low-energy particles, and so the spectrum (eq. [1]) has an exponential *low-energy cutoff* at

$$p_{\text{min}}(x) \approx \frac{1}{\kappa'} \int_0^x u dx \sim V_{\text{shock}} x / \kappa'. \quad (2)$$

For the Bohm diffusion, we have

$$p_{\text{min}}/mc \approx (V_{\text{shock}}/c) B_\mu (x/10^{12} \text{ cm}), \quad (3)$$

where B_μ is the magnetic field in units of microgauss. This low-energy decay can explain why the same MC can be visible in the TeV energy range and invisible in the GeV range. Let the nearest edge of an adjacent MC be upstream of the shock at a distance $x = x_{\text{MC}}$, such that $1 \text{ GeV}/c < p_{\text{min}}(x_{\text{MC}}) < p_{\text{max}}$. This low-energy cutoff p_{min} is shown in Figure 1 and will be dis-

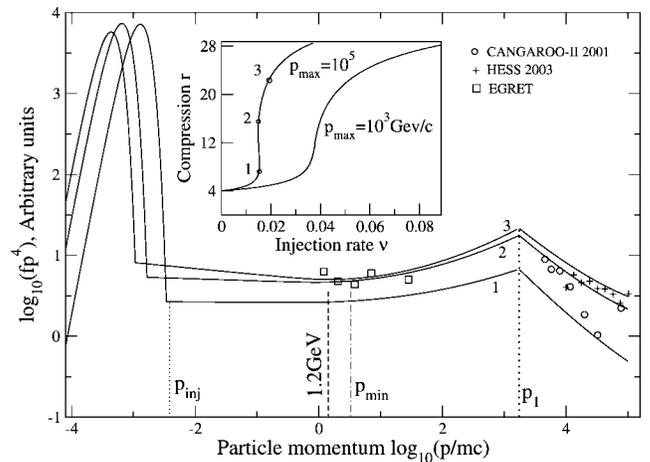


FIG. 1.—*Inset*: Response of the shock structure to the particle acceleration. The flow compression ratio r is shown as a function of particle density n_{CR} injected into the acceleration from the thermal distribution calculated for two maximum momenta p_{max} and the shock Mach number $M = 80$. The injection parameter $\nu \sim (cp_{\text{inj}}/mV_{\text{shock}}^2)n_{\text{CR}}/n_1$, where n_1 is the plasma density upstream of the shock. The details of these calculations and those of the spectra shown in the main figure can be found in Malkov & Drury (2001). *Main figure*: Spectra of accelerated particles behind the shock front, for $p_{\text{max}}/mc = 10^5$. Three solutions correspond to the points 1–3 on the compression-injection diagram in the inset. Note that the test particle (linear) spectrum would be represented by a horizontal line. The break energy (momentum) is at $p/mc = 1.8 \times 10^3$. The CANGAROO-II (Enomoto et al. 2002) and HESS points are adopted from Aharonian et al. (2004), while the EGRET (Hartman et al. 1999) points are adopted from Reimer & Pohl (2002). Vertical lines indicate the injection momentum (separating thermal and nonthermal particles), the 1.2 GeV proton energy threshold of π^0 production, the possible low-energy cutoff $p_{\text{min}}(x)$, and the spectral break p_1 (see text).

cussed below.⁴ The last condition means that the leading edge of the CR precursor (filled with TeV protons) has already penetrated into the MC, but the subshock itself (with the GeV particles ahead of it) still has not. Obviously, CANGAROO and HESS could detect the proton TeV emission while EGRET could not, because of the low density inside the wind bubble that the subshock is located in. The strong X-ray emission expected when the subshock crashes into the dense MC will not yet be visible either.

3. HIGH-ENERGY SPECTRAL BREAK

In the presence of weakly ionized dense gas, the particle and emission spectra undergo significant modifications in the TeV energy range, where a spectral break can form. According to equation (1), the accelerated particles occupy an extended precursor of the size

$$l_{\text{CR}} \sim \kappa(p_{\text{max}})/V_{\text{shock}} > r_g(p_{\text{max}})c/V_{\text{shock}} \quad (4)$$

ahead of the shock. Here r_g is the particle gyroradius. One can estimate l_{CR} as $l_{\text{CR}} \sim (p_{\text{max}}/mc)(c/V_{\text{shock}})B_\mu^{-1}10^{12} \text{ cm}$. Thus, the shock precursor may be as long as 10^{18} cm for $p_{\text{max}} \sim 10 \text{ TeV}$. Therefore, the accelerated particles start to interact with an MC before it becomes significantly ionized by the shock wave or the ionizing precursor (Draine & McKee 1993). Hence, they propagate in the MC under conditions of strong ion-neutral collisional damping of the self-generated Alfvén waves that are needed to

³ Note that this cutoff is usually ignored in shock acceleration models since only the downstream solution is considered. When the dense gas is present upstream of the shock, this cutoff should be included in the calculation of γ -radiation.

⁴ We have chosen the following values for the parameters in eq. (3): $V_{\text{shock}} = 1000 \text{ km s}^{-1}$, $B_\mu = 3$, and the distance from the subshock to the MC, $x = x_{\text{MC}} \approx 7 \times 10^{15} \text{ cm}$. Note that for the visibility of the TeV and higher energy protons, it is sufficient that $x_{\text{MC}} < 10^{17} \text{ cm}$.

confine accelerated particles. More importantly, there is a gap in wavenumber space at $k_1 < k < k_2$ where the waves do not propagate (Kulsrud & Pearce 1969; Zweibel & Shull 1982). Here it is critical to realize that waves *literally do not exist*, as opposed to simply being damped by collisions (Drury et al. 1996). The above wave evanescence range is bounded by $k_1 = \nu_{i-n}/2V_A$ and $k_2 = 2(\rho_i/\rho_0)^{1/2}\nu_{i-n}/V_A$, where $\rho_i/\rho_0 \ll 1$ is the ratio of the ion to neutral mass density, ν_{i-n} is the ion-neutral collision frequency, and $V_A = B/(4\pi\rho_0)^{1/2}$ is the Alfvén speed. The resonance condition for the wave generation and the particle's scattering off them is $k p_{\parallel}/m = \pm\omega_c$, where $\omega_c = eB/mc$ and p_{\parallel} is the parallel (to the magnetic field) component of particle momentum. Therefore, particles having $p_1 < |p_{\parallel}| < p_2$, where

$$p_1 = 2V_A m \omega_c / \nu_{i-n}, \quad p_2 = \frac{1}{4} \sqrt{\frac{\rho_0}{\rho_i}} p_1 > p_1, \quad (5)$$

are not scattered by any waves, so that the confinement of all particles with $|p_{\parallel}| > p_1$ is dramatically degraded. We assume that the gap in $p_1 < |p_{\parallel}| < p_2$ is sufficiently broad, so that resonance broadening (e.g., Achterberg 1981) does not bridge it. We also assume that there is no significant background turbulence at the scales $\lambda > 2\pi/k_1$ that could reduce particle diffusivity to a limit that is not significantly higher than the Bohm value. For the parameters used in our calculations below, $k_1 \sim 10^{-14} \text{ cm}^{-2}$. Then, particles with $|p_{\parallel}| > p_1$ will escape from the MC upstream of the shock along the magnetic field at a speed comparable to c , or at least their confinement time to the shock will be much shorter than those with $|p_{\parallel}| < p_1$. Only the latter particles will generate π^0 -mesons and γ -emission efficiently in the MC. Their pitch angle distribution for $p > p_1$, however, is limited to the interval $|\mu| < p_1/p$. Therefore, the contribution to the γ -emission of particles with momentum $p > p_1$ is reduced by the phase volume filling factor $\mu_{\text{crit}} = p_1/p$. The resulting emission spectrum is thus one power steeper than in the standard calculations (e.g., Berezhinsky & Ptuskin 1989; Drury et al. 1994; Naito & Takahara 1994) based on the isotropic particle distribution. The latter yields the γ -spectrum that reproduces the energy spectrum of the particles up to about $0.1c p_{\text{max}}$, where it declines. Hence, the energy spectrum of the γ -emission must be the same as that of the particles, proportional to ϵ_{γ}^{-s} , for the photon energy $\epsilon_{\gamma} < \epsilon_{\text{br}} \sim 0.1c p_1$ (particle momenta $p < p_1$), and it must scale proportional to ϵ_{γ}^{-s-1} for $\epsilon_{\gamma} \geq \epsilon_{\text{br}}$ up to about $0.1c p_{\text{max}}$ (particle momenta $p_1 < p < p_{\text{max}}$). The break energy ϵ_{br} can be estimated using equation (5) for p_1 by substituting $\nu_{i-n} = n_0 \langle \sigma V \rangle$, where σ is the cross section of the ion-neutral collisions and V is the collision velocity averaged over a thermal distribution. Using an approximation of Kulsrud & Cesarsky (1971) for $\langle \sigma V \rangle$, p_1 can be estimated as

$$p_1/mc \approx 16B_{\mu}^2 T_4^{-0.4} n_0^{-1} n_i^{-1/2}, \quad (6)$$

where T_4 is measured in the units of 10^4 K , and n_0 and n_i (number densities corresponding to the mass densities ρ_0 and ρ_i) in units of cm^{-3} .

To illustrate these results, we consider three different acceleration regimes, corresponding to the three substantially different shock compression ratios r , shown by the points 1–3 in the inset to Figure 1. (Here r means a total shock compression, which is the adiabatic compression across the precursor times the subshock jump.) As can be seen from this plot, the shock

compression is difficult to calculate accurately because of its sharp dependence on the injection rate (usually not well known) and other parameters, such as the maximum momentum. We discuss this spectrum in more detail in the next section.

4. DISCUSSION AND CONCLUSIONS

In this Letter we have considered the *upstream* particle spectrum since this is necessary for interpretation of cases in which a shock is expanding into a low-density pre-supernova wind bubble and is approaching a denser material such as a swept-up shell or an MC. Perhaps the most discussed SNR of this kind is the RX J1713.7–3946 claimed by the CANGAROO team to be a long-anticipated proton super-TeV accelerator (Enomoto et al. 2002). A significant part of the TeV emission detected by the CANGAROO and HESS (Aharonian et al. 2004) instruments comes from the northwestern rim of the remnant where the interaction with a molecular cloud is believed to take place (e.g., Slane et al. 1999; Hiraga et al. 2005). Therefore, these observations are pertinent to the subject of this Letter.

To demonstrate that the observed TeV spectra are consistent with the mechanisms suggested in this Letter, we put the calculated upstream *proton* spectra on one plot with the CANGAROO/HESS and EGRET *photon* fluxes that would be radiated by these protons. Since the emission generated by protons has typically an order of magnitude lower energy, we upshifted the *observed* emission energy accordingly in Figure 1. As the spectrum in the range $1 \text{ GeV } c^{-1} < p < p_1$ is considerably flatter than in the case of the linear theory, its magnitude at $p = p_1$ is an order of magnitude higher for the same injection rate. This lowers the ambient gas density required to produce the same TeV emission as computed by Enomoto et al. (2002) using the linear spectrum. In addition, this allows us to accommodate the EGRET points, should they belong to the same object (Reimer & Pohl 2002). However, because of the controversy about the distance to the remnant (6 kpc vs. 1 kpc; Slane et al. 1999; Fukui et al. 2003) and other uncertainties, it is impossible to present detailed normalized fits of the photon flux in this Letter.

The form of the spectrum is marked by increasing the spectral index by one at the break momentum $p = p_1$ (Fig. 1). This is crucial to fitting the observed spectra without imposing a specific form and value of the energy cutoff. The latter procedure would give only a poor fit (e.g., Reimer & Pohl 2002). Note that there are two CANGAROO points that are not in good agreement with both the HESS and the theoretical spectrum. It should be noted, however, that any disagreement between the three sets of spectral points is substantially enhanced in this particular spectrum format (the particle phase density is multiplied by p^2). Except for these two points, the agreement is remarkably good. Interestingly enough, the agreement is excellent for a subset of HESS points with the lowest and highest energy points excluded.

Unlike the power-law index, it is more difficult to constrain the parameters determining the position of the break on the spectrum given by equation (6) because of the poor information about the target gas for p - p reactions (MC). For the particular case shown in Figure 1, we have chosen such a combination of parameters in equation (6) that p_1 amounts to $p_1 \sim 1.8 \text{ TeV } c^{-1}$. MCs in general are known to be “clumpy,” with an interclump gas density of $5\text{--}25 \text{ cm}^{-3}$ and a less than 10% filling factor (see, e.g., Chevalier 1999, Bykov et al. 2000, and references therein). The results shown in Figure 1 are obtained for the following values of parameters in equation (6): $B_{\mu} \approx$

14, $T_4 \approx 0.01$, $n_0 \approx 23$, and $n_i \approx 0.23$, which yields $p_1/mc \approx 1.8 \times 10^3$. By contrast, in the model of Ellison et al. (2001), a much lower target density is assumed since its authors do not consider the possibility that the CR precursor could reach the dense gas while the shock itself is still in the wind bubble. Therefore, they concluded that the p - p reactions do not contribute significantly to the TeV emission because of the lack of target protons. In contrast to the conclusion of Ellison et al. (2001) and to that of Enomoto et al. (2002), the most recent HESS observations allow their authors (Aharonian et al. 2004) to assume that both protons and electrons contribute significantly to the TeV emission.

Note that a complementary mechanism of suppression of the low-energy (GeV) emission has been suggested earlier by Aharonian & Atoyan (1996) and discussed recently in the context of SNR RX J1713.7–3946 by Uchiyama et al. (2003). This mechanism requires an impulsive release of accelerated particles at some distance from an MC (target) and the subsequent (energy-dependent) diffusive propagation of CRs to the target. By contrast, the mechanism discussed in this Letter is based on a quasi-stationary solution of the acceleration problem (eq. [1]), which implies that the accelerated particles are bound to the propagating shock front via self-generated Alfvén waves. It is clear, however, that in both cases the suppression of the low-energy emission is based on a slower diffusion of low-energy particles. Note that Lazendic et al. (2004) also discussed qualitatively the same effect. It is also important to mention that GeV emission may not be suppressed all over the remnant, and it was demonstrated by Butt et al. (2001) to be likely of proton origin. Obviously, the spectral modifications considered in this Letter are equally applicable to electrons of similar rigidity.

It should be pointed out that our model in its current version does not provide a complete fit to the data, particularly in the X-ray and radio energy bands. The TeV-GeV fluxes are given in arbitrary units, so only the *form* of the spectrum (including

possible GeV signal) is provided here. A complete fit would require the convolution of the proton spectrum with appropriate emissivities given the densities and the distance. The thermal peak in Figure 1 is a Maxwellian, approximately normalized relative to the high-energy part of the spectrum, in accordance with the calculated downstream temperature without turbulent heating. A more accurate calculation of the thermal peak would require an adequate injection model and turbulent gas heating in the precursor (e.g., Berezhko et al. 1996; Malkov & Drury 2001; Kang et al. 2002). Such calculations of the thermal X-ray emission should be tested specifically against very low observed upper limits. One *potentially* observable prediction of our model is the break in the pitch angle-averaged particle spectrum at $p = p_1$ that would be produced by almost instant losses along the field lines of all particles with $|p_{\parallel}| > p_1$ once they enter a partially ionized gas with significant ion-neutral collisions. This break may very well be in the currently “obscure” energy range between the EGRET and the ground-based Cerenkov telescope energy bands. The next generation of space gamma telescopes, such as *GLAST*, will be able to explore this energy range.

The principal results of this Letter, which are the spectrum softening by one power above the spectral break and the possibility of a low-energy cutoff, clearly show that these physical phenomena need to be included in the models to conclusively differentiate between the nucleonic and leptonic sources of the TeV emission from the remnants nearby molecular clouds such as RX J1713.7–3946. Previous claims to the contrary have ignored necessary refinements in the DSA theory beyond the level of test particle theory.

We thank Felix Aharonian and Heinz Völk for their helpful discussions as well as an anonymous referee who provided useful comments on the manuscript. Support under NASA grant ATP03-0059-0034 and under US DOE grant FG03-88ER53275 is gratefully acknowledged.

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