The multi-band nonthermal emission from the supernova remnant RX J1713.7-3946

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ABSTRACT
Nonthermal X-rays and very high-energy (VHE) $\gamma$-rays have been detected from the supernova remnant (SNR) RX J1713.7-3946, and especially the recent observations with the Suzaku satellite clearly reveal a spectral cutoff in the X-ray spectrum, which directly relates to the cutoff of the energy spectrum of the parent electrons. However, whether the origin of the VHE $\gamma$-rays from the SNR is hadronic or leptonic is still in debate. We studied the multi-band nonthermal emission from RX J1713.7-3946 based on a semi-analytical approach to the nonlinear shock acceleration process by including the contribution of the accelerated electrons to the nonthermal radiation. The results show that the multi-band observations on RX J1713.7-3946 can be well explained in the model with appropriate parameters and the TeV $\gamma$-rays have hadronic origin, i.e., they are produced via proton-proton (p-p) interactions as the relativistic protons accelerated at the shock collide with the ambient matter.

Key words: radiation mechanisms: non-thermal – supernova remnants – gamma-rays: theory – ISM: individual(RX J1713.7-3946)

1 INTRODUCTION
Supernova remnants (SNRs) are broadly believed to be acceleration sites of the Galactic cosmic rays. X-ray observations can provide an indication of electrons being accelerated up to multi-TeV energies and very high-energy (VHE) observations indicate that the particles would be accelerated up to hundreds of TeV or more in the SNRs. However, the origin of the VHE $\gamma$-rays from SNRs is still uncertain because the TeV $\gamma$-rays from each source can usually be explained either by hadronic models in which they are produced via p-p interactions or by leptonic ones in which they are from inverse Compton scattering of the parent electrons (e.g., Berezhko & Völk 2006; Aharonian et al. 2007; Zhang & Fang 2007, 2008; Yamazaki et al. 2008; Fang & Zhang 2008; Fang et al. 2008; Tanaka et al. 2008; Liu et al. 2008). Detailed multi-band observations in X-rays, TeV $\gamma$-rays and especially in the MeV/GeV band with the Fermi Gamma-ray Space Telescope (FGST) satellite are important to eliminate the uncertainty on the origin of TeV $\gamma$-rays from SNRs.

RX J1713.7-3946 (G347.3-0.5) is a shell-type SNR with faint radio emission (Lazendic et al. 2004) and strong nonthermal X-ray emission (Slane et al. 1999). TeV $\gamma$-rays from the SNR shell were first detected by CANGAROO (Muraishi et al. 2000) and confirmed by CANGAROO-II (Enomoto et al. 2002) and H.E.S.S. (Aharonian et al. 2006). Recently, Aharonian et al. (2007) reported the three-year H.E.S.S. observations on the remnant. The combined data significantly increase statistics and the VHE spectrum extends over three orders of magnitude up to energies $\sim$ 100 TeV. The X-ray observations on the SNR have been performed with Suzaku and a wide-band X-ray spectrum (0.4–40 keV) with high statistics has been shown by combining the X-ray Imaging Spectrometer (XIS) and the Hard X-ray Detector (HXD) spectrum (Takahashi et al. 2008; Tanaka et al. 2008). The X-ray spectrum shows a clear cut-off shape, which allows the energy spectrum of the parent electrons to be more clearly investigated.

In this paper, we investigate the multi-band nonthermal emission from RX J1713.7-3946 in the frame of nonlinear diffusive shock acceleration mechanism, which has been studied extensively both numerically (e.g., Ellison, Baring & Jones 1996; Berezhko & Völk 1997; Kang & Jones 2006; Ellison et al. 2007) and semi-analytically (e.g., Malkov & Drury 2001; Blasi, Amato & Caprioli 2007; Amato, Blasi & Gabici 2008). The origin of the TeV $\gamma$-rays from the source had been numerically studied by Berezhko & Völk (2008) using the nonlinear kinetic theory of cosmic ray acceleration in SNRs. They shown that the recent high-energy observations with H.E.S.S. and Suzaku agree well with their previous study (Berezhko & Völk 2006) on the SNR and the hadronic origin of the TeV photons is more favored than the leptonic one. Moreover,
they argued that the non-thermal X-ray emission can correlate with the γ-ray one due to the correlation between the magnetic field amplification with the accelerated nuclear particles and the associated streaming instabilities (see details in Berezko & Völk 2008). Here we calculate the spectrum of the particles accelerated at shocks using the semi-analytical method proposed in Blasi (2002) and Blasi, Gabici & Vannoni (2003) and assume that the accelerated electrons have the same spectrum of the protons up to a maximum energy determined by synchrotron losses (Ellison et al. 2000), and then calculate the multi-band nonthermal photon spectrum from RX J1713.7-3946. The results show that the multi-band spectrum of the SNR can be well reproduced with appropriate parameters in the model and the observed TeV γ-rays are produced mainly via hadronic interactions.

Very recently, Morlino, Amato & Blasi (2008) calculated the high-energy spectrum for RX J1713.7-3946 in the context of the nonlinear particle acceleration process at shocks, which is similar to that using in this paper. However, our approach is different from Morlino, Amato & Blasi (2008). Firstly, the shape of the multi-band spectrum is sensitive to the Mach number of the shock; therefore, we investigate the nonthermal spectrum from the point of the Mach number and find the multi-band observations on the remnant can be well reproduced with appropriate parameters in the model. Secondly, they treated the cut off in the spectrum of electrons as \( \exp[-(E/E_{\text{max}})^2] \); however, we find the Suzaku observation can still be well reproduced with the conventional cut off as \( \exp[-(E/E_{\text{max}})] \) in our approach; Finally, the multi-band observations for the SNR consist well with the model results with the parameters (see Fig.3). \( T_0 = 10^7 \) K, which is argued to be the temperature of the bubble around the SNR, and \( M_0 = 8.0 \), corresponding to a shock speed of \( \sim 3000 \) km s\(^{-1} \), whereas a value of \( 10^6 \) K for \( T_0 \) is used in Morlino, Amato & Blasi (2008).

The structure of this paper is as follows. In \( \S 2 \), we briefly review the model used here and show our calculation results, and give some discussion and conclusions in \( \S 3 \).

### 2 THE MODEL AND RESULTS

The pitch-angle averaged steady-state distribution of the protons accelerated at a shock in one dimension satisfies the diffusive transport equation (Malkov & Drury 2001; Blasi 2002; Amato, Blasi & Gabici 2008).

\[
\frac{\partial}{\partial x} \left( D \frac{\partial f(x,p)}{\partial x} \right) - v \frac{\partial f(x,p)}{\partial x} + \frac{1}{3} \frac{\partial p}{\partial x} \frac{\partial f(x,p)}{\partial p} + Q(x,p) = 0,
\]

where the coordinate \( x \) is directed along the shock normal from downstream to upstream, \( D \) is the diffusion coefficient and \( v \) 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 \( (x = +\infty) \). 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

\[
Q_0(p) = \frac{\eta n_{\text{gas,0}} u_1}{4\pi p_\text{inj}^2} \delta(p - p_{\text{inj}}),
\]

where \( p_{\text{inj}} \) is the injection momentum, \( n_{\text{gas,0}} \) is the gas density at \( x = 0^+ \) and \( \eta \) is the fraction of particles injected in the acceleration process. With the injection recipe known as thermal leakage, \( \eta \) can be described as \( \eta = 4(R_{\text{sub}} - 1)E^{3/2}/\gamma^2 \). Blasi, Gabici & Vannoni (2003, Amato, Blasi & Gabici 2008), where \( R_{\text{sub}} = u_1/u_2 \) is the compression factor at the subshock and \( \gamma \) is a parameter of the order of 2–4 describing the injection momentum of the thermal particles in the downstream region \( (p_{\text{inj}} = E_{\gamma \text{ph}}/2) \). We use \( \gamma = 3.5 \) as in Amato, Blasi & Gabici (2008), \( E_{\gamma \text{ph}} = (2m_p k_B T_2)^{1/2} \) is the thermal peak momentum of the particles in the downstream fluid with temperature \( T_2 \), \( m_p \) is the proton mass and \( k_B \) is the Boltzmann constant. Assuming 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., \( T_2 = (\gamma_{\text{th}} M_0^2/R_{\text{tot}})[R_{\text{sub}}/R_{\text{tot}} - 1/R_{\text{tot}} + (1/\gamma_{\text{th}} M_0^2)(R_{\text{tot}}/R_{\text{sub}})^{\gamma-2}]T_0 \), where \( M_0 \) is the fluid Mach number far upstream, \( R_{\text{tot}} = u_0/u_2 \) is the total compression factor, \( \gamma_{\text{th}} \) is the ratio of specific heats \( (\gamma_{\text{th}} = 5/3 \) for an ideal gas).

RX J1713.7-3946 has been thought as a remnant of type II/1b supernova and is evolving in a bubble with a typical temperature \( \sim 10^7 \) K (e.g., Morlino, Amato & Blasi 2008). In this paper, we use \( T_0 = 10^7 \) K, which corresponds to a sound speed of \( \sim 370 \) km s\(^{-1} \), to calculate the multi-band flux for the SNR.

With the assumption that the diffusion is \( p \) dependent and therefore particles with larger momenta move farther away from the shock than those with lower momenta, only particles with momentum \( \gg p \) can reach the point \( x_p \) and thus the pressure of the accelerated particles at the point can be described as (Blasi 2002)

\[
P_{\text{CR,p}} = \frac{4\pi}{3} \int_{x_p}^{p_{\text{max}}} dp' p'^5 v(p') f_0(p') ,
\]

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 (Blasi 2002)

\[
f_0(p) = \left[ \frac{3R_{\text{tot}}}{R_{\text{tot}} U(p) - 1} \right] \frac{n_{\text{gas,0}}}{4\pi p_{\text{inj}}^2} \times \exp \left[ -\int_{p_{\text{inj}}}^{p_{\text{max}}} \frac{dp'}{p'} \frac{3R_{\text{tot}} U(p') - 1}{R_{\text{tot}} U(p') - 1} \right],
\]

where \( n_{\text{gas,0}} \) is the gas density far upstream \( (x = +\infty) \), \( p_{\text{max}} \) is the maximum momentum of the accelerated particles. We use \( p_{\text{max}} \sim 1.0 \times 10^5 m_p c \) in this paper, which is a typical value for an SNR with ambient magnetic strength \( \sim 100 \) μG with an average shock speed of \( \sim 5000 \) km s\(^{-1} \) for a young SNR with an age of \( \sim 1000 \) yr (Yamazaki et al. 2008). \( U(p) \) can be solved using an equation deduced from the conservation of the mass and momentum fluxes with the boundary condition \( U(p_{\text{inj}}) = R_{\text{sub}}/R_{\text{tot}} \) and \( U(p_{\text{max}}) = 1 \), and then a value of \( R_{\text{sub}} \) can be achieved by an iterative procedure to satisfy the boundary conditions (Blasi 2002).

Electrons accelerated at a shock are usually treated as test particles because they carry little momentum and have little influence on the shock structure. Therefore, their dis-
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Figure 1. The resulting electron (panel a) and proton (panel b) spectra and the spectral energy distribution of synchrotron emission of the electrons (panel c) and p-p interactions (panel d) of the protons for RX J1713.7-3946 with $d = 1$ kpc, $B_{\text{SNR}} = 100$ $\mu$G, $p_{\text{max}} = 1.0 \times 10^5$ $m_p c$, $E_{\text{max}, e} = 10$ TeV for $M_0 = 3$, $n_{\text{gas}, 0} = 6.05$ cm$^{-3}$, $K_{\text{ep}} = 1.32 \times 10^{-3}$ (dashed line); $M_0 = 5$, $n_{\text{gas}, 0} = 0.41$ cm$^{-3}$, $K_{\text{ep}} = 1.00 \times 10^{-4}$ (dotted line); $M_0 = 8$, $n_{\text{gas}, 0} = 0.13$ cm$^{-3}$, $K_{\text{ep}} = 3.82 \times 10^{-5}$ (solid line); and $M_0 = 12$, $n_{\text{gas}, 0} = 0.08$ cm$^{-3}$, $K_{\text{ep}} = 2.44 \times 10^{-5}$ (dash-dotted line). The ATCA radio data (Lazendic et al. 2004), Suzaku X-ray data (Tanaka et al. 2008), and H.E.S.S. (Aharonian et al. 2007) data from the years 2003, 2004 and 2005 are also shown.

distribution can not be obtained by general considering momentum and energy conservations. However, electrons and protons have the same acceleration rate if they have the same upstream diffusion length, so the electron and proton spectral shapes should be similar at superthermal energies (Ellison et al. 2000). As a result, the electrons have the same spectrum of the protons up to a maximum energy determined by synchrotron losses, and in this paper we simply use

$$f_e(x, p) = K_{\text{ep}} f(x, p) \exp(-E(p)/E_{\text{max}, e}),$$

where $E(p)$ is the kinetic energy of the electrons, $E_{\text{max}, e}$ is the cutoff energy due to the synchrotron losses, and the electron/proton ratio $K_{\text{ep}}$ is treated as a parameter.

Assuming the accelerated particles 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 via p-p interactions can be written as

$$Q(E) = 4\pi n_{\text{gas}} \int dE_p J_p(E_p) \frac{d\sigma(E, E_p)}{dE},$$

where $E_p$ is the proton kinetic energy, $n_{\text{gas}}$ is the ambient gas number density, and $J_p(E_p) = v p^2 f_0(p) dp / dE_p$ is the volume-average proton density and $v$ is the particles’ velocity. We use the differential cross-section for photons $d\sigma(E, E_p) / dE$ presented in Kamae et al. 2006 to calculate the hadronic $\gamma$-rays produced via p-p collisions. Finally, the photon flux observed at the earth can be obtained with

$$F(E) = \frac{V Q(E)}{4\pi d^2},$$

where $d$ is the distance from the earth to the source and $V$ is the average emitting volume of the source and can be estimated by $V \approx \left(4\pi/3\right) R_{\text{SNR}}^3 / R_{\text{rot}}$, here $R_{\text{SNR}}$ is the radius of the SNR (Ellison et al. 2004). Note that the emission from secondary $e^\pm$ pairs produced from p-p collisions is usually orders of magnitude smaller than that from the primary electrons and protons for a young SNR (Fang & Zhang 2008), thus we neglect the component from the secondary $e^\pm$ pairs.

The distance of RX J1713.7-3946 is uncertain and has been revised sometimes (Aharonian et al. 2006). The ASCA X-ray observation (Koyama et al. 1997) and NANTEN CO data (Fukui et al. 2003; Moriguchi et al. 2007) indicate the SNR has a distance of $\sim 1$ kpc corresponding to an age of $\sim 1000$ yr and we use this value in this paper. The magnetic field in the diffuse regions where the bulk of the synchrotron emission is produced is $\geq 100$ $\mu$G in order to explain the X-ray flux ratio between the diffuse and compact regions (Uchiyama et al. 2007; Tanaka et al. 2008). We use $100$ $\mu$G to calculate the synchrotron emission of the accelerated electrons and the cutoff energy of the electrons must be $\sim 10$ TeV to well reproduce the X-ray spectrum observed with Suzaku.
Fig. 2. Comparisons of the resulting spectral energy distributions of p-p interactions for RX J1713.7-3946 for $M_0 = 8$, $p_{\text{max}} = 0.8 \times 10^5$ $m_p c$ (dotted line); $p_{\text{max}} = 1.0 \times 10^5$ $m_p c$ (solid line); $p_{\text{max}} = 1.5 \times 10^5$ $m_p c$ (dashed line); $p_{\text{max}} = 2.0 \times 10^5$ $m_p c$ (dash-dotted line) with the H.E.S.S. data points (Aharonian et al. 2007).

Fig. 3. The resulting spectral energy distribution of synchrotron emission (dashed line), inverse Compton scattering (dotted line) and p-p interactions (solid line) for RX J1713.7-3946 with $M_0 = 8$, $p_{\text{max}} = 1.3 \times 10^5$ $m_p c$, $n_{\text{gas,0}} = 0.12$ cm$^{-3}$, $K_{\text{ep}} = 3.92 \times 10^{-5}$. Others are the same as Fig. 2.

Fig. 4. Clear comparisons of the model results with the observed data with Suzaku (upper panel) and H.E.S.S.. Others are the same as Fig. 2.

The maximum energy of the accelerated electrons for the SNR RX J1713.7-3946 is limited due to the strong synchrotron losses in our model, so the shape of the synchrotron emission is nearly constant with different maximum energies of the protons. The influence of $p_{\text{max}}$ on the spectrum of p-p collisions is shown in Fig. 2. Obviously, the TeV observations can be well reproduced with $p_{\text{max}}$ around $1.0 \times 10^5$ $m_p c$ and the spectrum with $p_{\text{max}} = 2.0 \times 10^5$ $m_p c$ relatively deviates from the high-energy observations with H.E.S.S. by Morlino, Amato & Blasi (2008).
Bremstrahlung is negligible even compared with the inverse Compton scattering. Obviously, the observed TeV γ-rays are from hadronic interactions as the relativistic protons collide with the ambient matter.

3 DISCUSSION AND CONCLUSIONS

RX J1713.7-3946 is a well-observed shell-type SNR in the radio, X-ray and TeV γ-ray bands. Relatively strong magnetic field with strength \( \approx 100 \, \mu \text{G} \) for the regions where the bulk of synchrotron emission is produced has been deduced from the observation in X-rays. Especially, the observation with Suzaku gives a wide-band spectrum with energies from 0.4 to 40 keV, and the clear cutoff shape of the observed X-ray spectrum can constrain the model parameters better than before. Based on the semi-analytical approach to the particle acceleration process at a shock, we investigated the multi-band nonthermal spectrum for the SNR by taking the contribution of electrons into account. The observed multi-band nonthermal spectrum for the SNR can be well reproduced in the model with \( K_{cp} = 3.92 \times 10^{-4} \), \( M_0 = 8.0 \), corresponding to a shock speed of \( \approx 3000 \, \text{km s}^{-1} \) for \( T_0 = 10^7 \, \text{K} \), \( p_{\text{max}} = 1.3 \times 10^5 \, \text{m}\text{p} \), and the maximum energy of electrons due to the synchrotron loss is \( \approx 10 \, \text{TeV} \) in order to make the model result consistent with the observed X-ray spectrum can constrain the model parameters better than before. Based on the semi-analytical approach to the particle acceleration process at a shock, we investigated the multi-band nonthermal spectrum for the SNR by taking the contribution of electrons into account. The observed multi-band nonthermal spectrum for the SNR can be well reproduced in the model with \( K_{cp} = 3.92 \times 10^{-4} \), \( M_0 = 8.0 \), corresponding to a shock speed of \( \approx 3000 \, \text{km s}^{-1} \) for \( T_0 = 10^7 \, \text{K} \), \( p_{\text{max}} = 1.3 \times 10^5 \, \text{m}\text{p} \), and the maximum energy of electrons due to the synchrotron loss is \( \approx 10 \, \text{TeV} \) in order to make the model result consistent with the X-ray observation. The corresponding energy contained by the accelerated protons is \( \approx 3 \times 10^{40} \, \text{erg} \), and about 15% of the explosion energy is transferred to protons with a usual explosion energy of \( \approx 2 \times 10^{52} \, \text{erg} \) (e.g., Berezhko & Völk 2004). The results show that the TeV γ-rays observed by H.E.S.S. are produced predominately via p-p interactions and the observed X-ray spectrum with Suzaku can be well explained as the synchrotron emission from the accelerated electrons (see Fig.3).

With \( n_{\text{gas},0} = 0.12 \, \text{cm}^{-3} \) and \( T_0 = 10^7 \, \text{K} \) for a young SNR with an age of \( \approx 1000 \, \text{yr} \), thermal X-rays from hot electrons should be detected from the remnant assuming that electrons and protons are in thermal equilibrium (e.g., Katz & Waxman 2008) and the lack of thermal X-ray emission from RX J1713.7-3946 seems to conflict with the above scenario in which the observed TeV γ-rays predominately have hadronic origin. However, the conflict can be excluded by assuming the electrons and protons are not in equilibrium and the electron temperature is significantly smaller than the proton’s (Morlino, Amato & Blasi 2008).

The possibility of leptonic origin of the TeV γ-rays has been investigated by many others. For example, Aharonian et al. (2006) and Yamazaki et al. (2008) found that the flat TeV emission detected by H.E.S.S. can not be reproduced with the one-zone model in which the electron acceleration and gamma-ray emission take place in the same region unless a relatively large energy density of the ambient soft field is used in the calculation. Alternatively, another population of electrons is necessary to reproduce the multi-band observations with inverse Compton scattering as the origin of the TeV γ-rays with relatively low magnetic field strength \( \approx 10 \, \mu \text{G} \) (Tanaka et al. 2008, Yamazaki et al. 2008), which is much less than the value deduced by Uchiyama et al. (2007) and Tanaka et al. (2008).

Now, we investigate the possible leptonic origin of the TeV photons with the model in Sec. 2. Fig.5 shows the resulting spectrum for \( B_{\text{SNR}} = 10 \, \mu \text{G} \), \( E_{\text{max},e} = 100 \, \text{TeV} \), \( n_{\text{gas},0} = 0.03 \, \text{cm}^{-3} \), \( K_{cp} = 1.23 \times 10^{-3} \). Others are the same as Fig.3.

In summary, the multi-wavelength spectrum of the SNR RX J1713.7-3946 from radio to γ-ray bands can be well modeled with \( B_{\text{SNR}} \approx 100 \, \mu \text{G} \) in the semi-analytical nonlinear case. VHE γ-rays from the SNR are produced predominately via the \( \pi^0 \) decay in p-p collisions and the X-ray spectrum obtained with Suzaku can be well explained as the synchrotron emission of the accelerated electrons. On the other hand, the radio, X-ray and VHE γ-ray observations can not be well explained in the case of leptonic origin of TeV γ-rays with lower magnetic field strength \( \approx 10 \, \mu \text{G} \) using the model in this paper.

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