DEPARTMENT OF THE ELECTRON DISTRIBUTION IN SUPERNOVA REMNANT RX J1713.7−3946 VIA A SPECTRAL INVERSION METHOD

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ABSTRACT

We show that the radio, X-ray, and γ-ray spectrum of the supernova remnant RX J1713.7−3946 can be accounted for with the simplest emission model, where all of these emissions are attributed to a population of relativistic electrons interacting with the cosmic microwave background radiation, IR interstellar photons, and a background magnetic field. Using a spectral inversion method, the parent electron distribution and its uncertainties are derived from the observed photon spectrum. These results are independent of the model of particle acceleration and strongly support the leptonic scenario for the TeV emission.

Key words: acceleration of particles – ISM: supernova remnants – methods: miscellaneous – radiation mechanisms: non-thermal

Online-only material: color figures

1. INTRODUCTION

Relativistic cosmic rays (CRs) with energies lower than the location of the “knee” of the CR spectrum (≈1015 eV) are commonly believed to be accelerated by the shock of supernova remnants (SNRs) in our Galaxy (Hillas 2005). Evidence of particle acceleration by shocks of SNRs first comes from radio observations of the remnants, where the radio emission is produced by relativistic electrons via the synchrotron process. The discovery of synchrotron X-ray emission from SNR 1006 reveals acceleration of TeV electrons by these shocks (Koyama et al. 1995). However, direct evidence of proton and ion acceleration up to the spectral “knee” remains elusive.

The discovery of synchrotron X-ray emission from SNR 1006 is thought to be produced by relativistic electrons via the synchrotron process. The radio, X-ray, and γ-ray spectrum of the supernova remnant RX J1713.7−3946 reveals acceleration of TeV electrons by these shocks (Koyama et al. 1995). However, direct evidence of proton and ion acceleration up to the spectral “knee” remains elusive.

Since the discovery of TeV emission from the shell-type SNR RX J1713.7−3946, there have been debates on the nature of the dominant TeV emission mechanism (Enomoto et al. 2002; Aharonian et al. 2004; Berezhko & Völk 2006; Uchiyama et al. 2007; Plage 2008; Butt et al. 2008; Liu et al. 2008; Katz & Waxman 2008; Fang et al. 2009; Zirakashvili & Aharonian 2010; Ellison et al. 2010; Abdo et al. 2011; Yuan et al. 2011; Inoue et al. 2011). The γ-rays from SNRs can be produced via a hadronic process, where neutral pions produced by inelastic collisions of energetic hadrons decay into γ-rays. Inelastic collisions of energetic hadrons decay into γ-rays.

Energetic leptons can produce γ-rays through inverse Compton (IC) scattering of low frequency background photons. Both energetic leptons and hadrons can also produce γ-rays through the bremsstrahlung process (Blumenthal & Gould 1970), which is negligible for SNR RX J1713.7−3946 (Aharonian et al. 2006). Multi-wavelength observations of photon emission from this SNR in combination with theoretical considerations and/or detailed numerical modeling have been used to argue either against or for the leptonic or hadronic scenarios (Enomoto et al. 2002; Katz & Waxman 2008; Plage 2008; Liu et al. 2008; Yamazaki et al. 2009; Ellison et al. 2010; Inoue et al. 2011). Despite all these explorations, the dominant TeV emission mechanism remains a matter of debate. Future neutrino experiments are expected to measure contributions to the observed TeV emission via the hadronic process (Vissani et al. 2011).

SNR RX J1713.7−3946 has been extensively studied from the radio, IR (Acero et al. 2009), X-ray (Koyama et al. 1997; Uchiyama et al. 2003; Cassam-Chena et al. 2004), GeV γ-ray (Abdo et al. 2011), to TeV γ-ray bands (Muraishi et al. 2000; Enomoto et al. 2002; Aharonian et al. 2006). The TeV γ-ray observations reveal a shell-like structure closely matching the radio and non-thermal X-ray shells (Aharonian et al. 2006). Most recently, observations made with the Fermi space telescope show that the spectrum of this source in the GeV band is very hard with a power-law photon index of Γ = 1.5 ± 0.1, which is difficult to accommodate in a hadronic scenario, but agrees well with the IC origin of γ-rays in the leptonic scenario (Abdo et al. 2011). On the other hand, by considering the potentially high inhomogeneity of the shocked interstellar medium (ISM), Inoue et al. (2011) argue that a hadronic model may still explain the Fermi observation.

However, even if future observations reveal γ-rays due to the hadronic process from isolated SNRs, this does not imply that they dominate the Galactic CR flux observed near the Earth. Ave et al. (2009) recently showed that the de-propagated Galactic CR source spectrum is much softer than that given by most diffusive shock acceleration models. Furthermore, as pointed out by Parizot et al. (2004), most of the SNRs are overlapping in superbubbles, where the particle acceleration mechanism may be quite different from that operating in isolated remnants (Ferrand & Marcowith 2010; Butt 2009).

Given the good spatial correlation between images made at different energy bands (Acero et al. 2009), certain distributions of energetic particles or mechanisms of particle acceleration are usually introduced to fit the spatially integrated broadband spectrum in all these previous studies. Different scenarios of the background radiation field and ISM are also considered. Uncertainties in the particle acceleration process at the SNR shocks, especially in the spatial diffusion coefficient of energetic particles and injection mechanisms of supra-thermal particles, have made the relevant studies inconclusive (Fan et al. 2010).

In this Letter, we show that the current observations, though very extensive, may not justify these sophisticated modelings. Assuming that the TeV γ-rays originate from the IC of the cosmic microwave background (CMB) radiation by relativistic electrons and an IR background with a blackbody spectrum suitable for the Galactic environment of the remnant,
we show that one can derive the parent electron distribution and its uncertainties directly from γ-ray observations with a well-established spectral inversion method (Section 2). It is also shown that by adjusting the magnetic field and the extrapolation of the parent electron distribution toward low and high energies, the radio to X-ray spectrum can also be reproduced. Therefore, the simplest emission model, where the broadband emission of SNR RX J1713.7–3946 is attributed to a population of relativistic electrons interacting with a background magnetic field, the CMB, and an IR photon background, can fully account for the radiation spectrum and gives direct constraints on the particle acceleration processes (Section 3). Although these results do not preclude some level of proton γ-rays being masked by the more intense electron γ-rays, improved spectral measurements are needed to go beyond such a simple model. The conclusions and implications of our study are given in Section 4.

2. SPECTRAL INVERSION METHOD

The primary goal of the study of astrophysical sources is to use characteristics of the observed emissions to probe the underlying physical processes. In general, the related radiation mechanisms are the first and most important processes to be studied. When the quality of the observational data is not sufficiently good, some forward modeling approach is usually taken to explain the relevant observations. The consequent results are usually model dependent since different assumptions can be introduced in the proposed models.

When the relevant radiative mechanisms are well established and the observed data have a high quality, a spectral inversion method may be used to derive the distribution of the parent particle distribution from the observed radiation spectrum. The parent particle distribution is more directly connected to the angle-integrated IC cross-section, respectively. Equation (1) can be rewritten as

\[ P(k) = \int d\gamma N(\gamma)p(\gamma, k), \] (2)

where \( P(\gamma, k) \) represents the spectral distribution of IC radiation of mono-energetic electrons with a Lorentz factor \( \gamma \).

In some astrophysical cases, \( n_{\text{ph}}(\epsilon) \) can be represented by the isotropic blackbody radiation \( n_{\text{ph}}(\epsilon) = 8\pi\epsilon^2/h^2c^3[\exp(\epsilon/e_c) - 1] \) where \( e_c = k_B T, \) and \( k_B, h, \) and \( T \) are the Boltzmann constant, the Planck constant, and the temperature of the radiation field, respectively. Then \( p(\gamma, k) \) in Equation (2) can be approximated as

\[ p(\gamma, k) = \frac{6\pi\sigma_Tm_e^2c^2\epsilon_c}{h^2\gamma^3} I(\eta_c, \eta_0) \] (3)

with the function \( I(\eta_c, \eta_0) \) given by

\[ I \approx \frac{\pi^2}{6} \eta_c \exp[-\frac{2\eta_0}{3\eta_c} - \frac{5}{4} \left( \frac{\eta_0}{\eta_c} \right)^{1/2}] \]
\[ + \frac{\pi^2}{3} \eta_c \eta_0 \exp[-\frac{2\eta_0}{3\eta_c} - \frac{5}{7} \left( \frac{\eta_0}{\eta_c} \right)^{0.7}], \] (4)

where \( \eta_c = \epsilon_c k/(m_e c^2) \) and \( \eta_0 \equiv k^2/[4\gamma m_e c^2(\gamma m_e c^2 - k)], m_e \) is the electron rest mass (Petruk 2009). With the approximation above, the double integral in Equation (1) for calculating the IC emissivity is simplified into a single integral as given by Equation (2). This simplification facilitates further steps in our spectral inversion method significantly. When there are multi-blackbody components, one can obtain an \( I \) for each temperature and add them together with the appropriate weight of their photon energy density to get the overall \( P \).

2.2. Matrix Formulation of the IC Emission

To derive the electron distribution \( N(\gamma) \) from the observed photon spectrum, which is proportional to \( P(k) \), one needs to use energy bins of the observed photon spectrum to discretize Equation (2) (Johns & Lin 1992):

\[ P(k_j) = \sum_{j=1}^{n} \left( \int_{\gamma_j}^{\gamma_{j+1}} N(\gamma)p(\gamma, k_j) d\gamma \right) \]
\[ = \sum_{j=2}^{n} \left( N(\gamma_j) \int_{\gamma_j}^{\gamma_{j+1}} p(\gamma, k_j) d\gamma \right), \] (5)

where \( k_0 \) corresponds to the highest energy of the observed photons and \( \gamma_j \) is the minimum Lorentz factor of electrons that can contribute to the IC γ-rays with an energy \( k_j \).

\( N(\gamma_j) \), which is what we will obtain directly from the inversion method, is the electron density in the Lorentz factor interval \( (\gamma_j, \gamma_{j+1}) \) averaged over \( p(\gamma, k_j) \).

So, for the \( n \) energy bins of the observed photons, \( P(k_j) \) forms an \( n \times 1 \) matrix, and the de-convolved electron distribution,
Figure 1. Left: the observed (circle) and smoothed (square) GeV and TeV \( \gamma \)-ray fluxes for RX J1713.7–3946. (Abdo et al. 2011; Aharonian et al. 2006). Right: the derived electron distribution with error bars. The red solid line represents the inter- and extrapolated electron distribution, which is used to calculate the synchrotron and IC radiation spectra in Figure 2. The blue solid line shows an analytical function, which can also reproduce the observed radiation spectrum. (A color version of this figure is available in the online journal.)

\[
\frac{\text{d}^2 F}{\text{d}E \text{d}t}(E) = \frac{N(E)}{\text{d}t},
\]

where \( N(E) \) is the electron density at energy \( E \). Then Equation (5) can be expressed in matrix form:

\[
P(k_i) = \sum_{j=i}^n \beta_{ij} \bar{N}(\gamma_j),
\]

where the IC power matrix \( \beta_{ij} \) is given by

\[
\beta_{ij} = \begin{cases} 
\int \gamma_j p(\gamma, k_i) \text{d}\gamma = \int \gamma_j p(\gamma, k_i) \text{d}\gamma \times 6\pi \sigma_T m_e^2 c^2 \varepsilon_c \times h^{-3}\gamma^{-2} I(\eta_c, \eta_0) & \text{for } j \geq i, \\
0 & \text{for } j < i.
\end{cases}
\]

Then the electron distribution can be derived by inverting this matrix equation

\[
\bar{N}(\gamma_i) = \sum_{j=i}^n \alpha_{ij} P(k_j),
\]

where the matrix \( \alpha_{ij} \) is the inverse of the matrix \( \beta_{ij} \):

\[
\alpha_{ij} = \begin{cases} 
\sum_{i=1}^{j+1} \beta_{i+1,j} \beta_{i,j}^{-1} & \text{for } j > i, \\
0 & \text{for } j = i, \\
\beta_{i,i}^{-1} & \text{for } j < i.
\end{cases}
\]

This kind of inversion method was first introduced by Johns & Lin (1992) to derive the parent electron distribution from the optically thin spectrum of bremsstrahlung photons. The IC of blackbody spectra has similar characteristics as the bremsstrahlung process after adopting the approximation discussed in Section 2.1. One therefore can readily adopt the formulae in this method. Note that \( \alpha_{ij} \) is given explicitly here, and there should be a minus sign in the original Equation (14) given by Johns & Lin (1992).

Since there are uncertainties in the observed \( \gamma \)-ray spectrum, the propagation of errors from the photon spectrum to the derived electron spectrum should be considered carefully. Fortunately, the matrix Equation (8) offers a very straightforward way of calculating the errors in the electron spectrum. The densities of electrons simply depend linearly on the photon fluxes; the errors of the electron densities are then given by

\[
\delta \bar{N}(\gamma_i) = \left[ \sum_{j=i}^n (\alpha_{ij} \delta P_j(k_j))^2 \right]^{1/2}.
\]

Thus, we can use this matrix formulation to obtain the electron distribution and errors from the observed photon fluxes and errors.

3. RESULTS

We now apply our inversion method to the GeV and TeV observations of SNR RX J1713–3946 by the Fermi-LAT and HESS (Abdo et al. 2011; Aharonian et al. 2006), respectively. Besides the CMB, we assume IR photons with a temperature of 30 K and an energy density of 1 eV cm\(^{-3}\) following Porter et al. (2006). Figure 1 shows the \( \gamma \)-ray spectrum of this SNR along with the resulting electron spectrum after applying the inversion method. Due to large errors and fluctuations of the observed \( \gamma \)-ray fluxes, negative electron densities are inferred for some energy intervals, which is clearly not physical but mathematically expected. To address this issue, a running smooth of the observed fluxes is done before applying the inversion method and the corresponding data are indicated by the squares in the figure. Even with such a smoothing, the error of the derived electron density is still large in some energy bins. Future observations with improved \( \gamma \)-ray flux density data will give a better electron spectral measurement.

To verify the validity of this method, one may calculate the IC and synchrotron spectra of the obtained electron distribution and compare them with observations. To do this properly, one first needs to interpolate the obtained electron spectrum since the energy bins are wide and the radiation spectra are sensitive to spectral details. We use a second-order polynomial to do the interpolation. To calculate the synchrotron spectrum, one also needs to specify the magnetic field and do the extrapolation of the electron distribution toward low and high energies. We assume power-law distributions for these extrapolations with the power-law indices as free parameters. By adjusting the magnetic field and the two power-law indices, one can fit the observed radio to TeV spectrum, as shown in Figure 2. For the best fit, the value of the magnetic field \( B = 15 \mu \text{G} \) and the values of the low- and high-energy end electron spectral indices are 2.1 and 10, respectively. This smooth electron distribution is shown as the red solid line in the right panel of Figure 1.

4. DISCUSSIONS AND CONCLUSIONS

With a spectral inversion method, we show full consistency of the simplest leptonic model for the radio to TeV spectrum
of SNR RX J1713.7−3946. The model does not prescribe the particle acceleration process and assumes only the CMB and an IR background as the seed photons for the IC scatter. The current observations, though extensive, therefore may not justify very sophisticated modeling of this source, and there is no prominent evidence of emission from energetic hadrons. The errors of the derived electron distribution are large and the resulting electron distribution can be readily fitted with a simple analytical function: \[ \gamma^{-2} \exp \left[-(\gamma/1.3 \times 10^7)^{6/5}\right] \] (blue solid line in the right panel of Figure 1), which also fits the overall radiation spectrum (blue lines in Figure 2). Although the difference between this analytical function and the distribution obtained from the interpolation and extrapolation of the derived electron densities appears to be prominent, it is not statistically significant due to these large errors.

These results have not taken into account the effect of optical background photons. Inclusion of this component, though more involved, is straightforward. Actually, even the adoption of blackbody spectra is not necessary. With the blackbody background photon spectrum, one may obtain some analytical expressions to better appreciate these results. For the spectral inversion method to be applicable, one just requires that, for a given Lorentz factor of electrons, the IC spectrum cut off sharply at high energies so that the IC cross-section may be represented by a triangle matrix. To estimate the effect of the optical background photons, we derive the electron distribution assuming the CMB alone. With a lower overall photon energy density, the inferred magnetic field is only 8.5 \( \mu G \), which is expected. The analytical approximation of the electron distribution is very similar except that the cutoff Lorentz factor changes from \( 1.3 \times 10^7 \) to \( 1.6 \times 10^7 \), which is caused by the higher energy of IR photons than that of the CMB. The spectral indices of the electron distribution extrapolated to low and high energies are 2.2 and 10, respectively, which are essentially the same. Therefore, with an extra optical photon background, we expect that the magnetic field increases even more and the cutoff energy of the electron distribution decreases slightly.

The analytical function is similar to those used in previous more quantitative studies (Fan et al. 2010; Yuan et al. 2011). However, a \( \chi^2 \) evaluation of the goodness of the model may not be justified for the following reasons: (1) there are systematic errors in the observed X-ray and \( \gamma \)-ray fluxes; (2) the \textit{Suzaku} X-ray spectrum is obtained from a part of the remnant and rescaled to give the overall fluxes (Tanaka et al. 2008), which may not be well justified due to the asymmetry of the source (Acero et al. 2009); (3) the complex source structure also betrays the simple one zone emission model (Acero et al. 2009), and both the magnetic field and the electron distribution may vary significantly across the remnant; (4) the background radiation field is not well known, which constitutes another systematic uncertainty; and (5) the particle acceleration process can be intrinsically complex without simple distributions of the acceleration particles (Petrosian & Liu 2004; Mewaldt et al. 2001; Chang et al. 2008; Butt 2009; Ferrand & Marcowith 2010; Adriani et al. 2011). Nevertheless, the method can be used for other sources where the emission is dominated by an optically thin IC process.

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5 Although it is well established that there are filaments of strong magnetic field in SNRs (Uchiyama et al. 2007), the filling factor of these filaments is usually low and their contributions to the spatially integrated spectrum are consequently low. Our simple one zone model for the bulk spectrum of the source is therefore justified. However, for studies directly related to these filaments, the inhomogeneity of the magnetic field must be considered (Bykov et al. 2009).
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