Radial Profiles of Non-thermal Emission from Supernova Remnant RX J1713.7-3946

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Abstract

Supernova remnant RX J1713.7-3946 has exhibited the largest surface brightness and a detailed spectral and shell-type morphology, and is one of the brightest TeV sources. The recent H.E.S.S. observation of RX J1713.7-3946 revealed a broken power-law GeV–TeV gamma-ray and a more extended gamma-ray spatial radial profile than in the X-ray band. Based on the diffusion shock acceleration model, we solve spherically symmetric hydrodynamic equations and particle transport equations, and investigate the multi-band non-thermal emission of RX J1713.7-3946 and radial profiles of its surface brightness for two selected zones in the leptonic scenario for gamma-ray emission. We found (1) the diffusion coefficient has a weak energy dependence, and the Kolmogorov type is favored; (2) the magnetic field strength can vary linearly or nonlinearly with radius for different surrounding environments because of possible turbulence in the shock downstream region, and compressional amplification is likely to exist at the shock front; (3) the non-thermal photons from radio to X-ray bands are dominated by synchrotron emission from relativistic electrons if the GeV–TeV gamma-rays are produced by inverse Compton scattering from these electrons interacting with the background photons; then the X-ray and gamma-ray radial profiles can be reproduced except for the more extended gamma-ray emission.

Unified Astronomy Thesaurus concepts: Theoretical models (2107); Radiative processes (2055); Non-thermal radiation sources (1119); Gamma-rays (637); Supernova remnants (1667)

1. Introduction

Supernova remnants (SNRs) are considered to be well-known accelerators of Galactic cosmic rays, while cosmic rays below the knee energy (∼10^{15} eV) are thought likely to come from these SNRs (Blasi 2013). Coincidentally, cosmic-ray particles could be effectively accelerated to such high energy by diffusive shock acceleration (DSA), which results in a power-law distribution of particles (e.g., Bell 1978; Blandford & Eichler 1987; Malkov & Drury 2001). In view of the excellent observation results of spectral and morphological features of young SNRs, the synchrotron X-ray emission observed from young SNRs is manifest in the presence of multi-TeV energy electrons, which naturally confirms the deductions of the DSA. Based on the DSA mechanism, the multi-band emission from radio to gamma-ray bands can be from electron synchrotron radiations, inverse Compton scattering (ICS), and non-thermal bremsstrahlung emission (leptonic scenario) or gamma-ray emission from the π^0-decay process with collisions between cosmic rays and background protons (hadronic scenario). However, it is still controversial that gamma-rays are produced by either a hadronic or leptonic (or hybrid) procedure. To date, many details of the DSA mechanism are also still unclear, such as the acceleration and injection efficiencies of accelerated particles, the maximum energy of cosmic rays accelerated by supernova shocks, as well as the roles of particle diffusion and magnetic field strength.

The SNR RX J1713.7-3946 is a well-known source for study of the DSA mechanism on account of detailed observations of radio, X-ray, and gamma-ray emission components (e.g., Koyama et al. 1997; Cassam-Chenaï et al. 2004; Tanaka et al. 2008; Acero et al. 2009; Abd et al. 2011; Aharonian et al. 2004, 2006, 2007; H.E.S.S. Collaboration et al. 2018); it should be an efficient cosmic ray accelerator. Pfeffermann & Aschenbach (1996) first discovered RX J1713.7-3946 from ROSAT X-ray observations, and Wang et al. (1997) judged that RX J1713.7-3946 was a remnant of the AD393 guest star according to the ROSAT observation, the historical records, as well as the visual position, distance, and age. It can be inferred that its age should be ∼1625 yr. A distance of 1 kpc was derived by Koyama et al. (1997) by means of X-ray measurements of the column density toward this source, and this also agrees with the estimated result from new high-resolution CO millimeter-wave observations (Fukui et al. 2003).

ASCA observations indicated that the X-ray emission from RX J1713.7-3946 is predominantly non-thermal, the line emission from the SNR interior was not detected, and an upper limit on the mean density around the remnant of less than 0.3 cm^{-3} was set considering the lack of thermal emission (Slane et al. 1999). Subsequently, a stringent constraint on the post-shock gas density was given with a value of ≤0.8 cm^{-3} in view of the absence of thermal X-ray emission (Tanaka et al. 2008). ROSAT and ASCA images are resolved with Chandra into bright filaments and fainter diffuse emission, which shows good correspondence with the radio morphological structure, and provides strong proof that the same population of electrons is responsible for the synchrotron emission in radio and X-ray bands in the northwestern region of the remnant (Lazendic et al. 2004). In addition, the observations of Chandra, XMM-Newton, and Suzaku (Uchiyama et al. 2003; Cassam-Chenaï et al. 2004; Hiraga et al. 2005; Takahashi et al. 2008; Tanaka et al. 2008) also proclaimed that the X-ray emission is predominantly from the synchrotron component without evidence of a thermal X-ray component. Suzaku measurements have clearly shown a power-law spectrum with a photon index of ∼2 and a smooth cutoff around a few keV; the hard X-ray spectrum from Suzaku HXD up to 40 keV has also been well described by a power-law form with a photon index of ∼3,
which is steeper than that measured with energies below \( \sim 10 \text{ keV} \). Recently, the INTEGRAL 17–120 keV spectrum of RX J1713.7-3946 was given with a power-law continuum with photon index of \( \sim 3 \), which is also softer than the value below \( \sim 10 \text{ keV} \); it is obvious that the spectrum becomes gradually steeper with increasing energy (Kuznetsova et al. 2019). Tsuji et al. (2019) showed spatially resolved non-thermal X-ray emission up to 20 keV with NuSTAR; the photon index is 2.15 and the cutoff energy is 18.8 keV in their model. They found that the cutoff energy seems to be variable, from 0.6 to 1.9 keV; to some extent, the cutoff shape can also give us some indication about the diffusion type. Katsuda et al. reported the indication about the diffusion type. Katsuda et al. (2015) reported the first evidence for thermal X-ray line emission from RX J1713.7-3946; these lines can be explained as the thermal emission from reverse-shocked supernova ejecta rather than swept-up interstellar medium or circumstellar medium (CSM); the progenitor of this remnant was a relatively low-mass star (\( \leq 20 \, M_\odot \)), and RX J1713.7-3946 is inferred to be a result of an SN Ib/c whose progenitor was a member of an interacting binary.

The observed gamma-ray energy spectrum of RX J1713.7-3946 has covered five orders of magnitude in energy from combined Fermi-LAT and H.E.S.S. observations. RX J1713.7-3946 was first detected in very-high-energy (VHE) gamma-rays by the CANGAROO collaboration (e.g., Muraishi et al. 2000; Enomoto et al. 2002). Afterwards, the H.E.S.S. Collaboration confirmed that the VHE gamma-ray radiation comes from the SNR shell and presented a resolved VHE gamma-ray image; later observations provided much detailed information about morphology, radial profiles, and the VHE gamma-ray energy spectrum (e.g., Aharonian et al. 2004, 2006, 2007; H.E.S.S. Collaboration et al. 2018). In the GeV energy range, Abdol et al. (2011) investigated the gamma-ray emission from RX J1713.7-3946 with Fermi-LAT. It was shown that the spectral index in this band is very hard with a photon index of 1.5 \( \pm 0.1 \), which is well in agreement with leptonic emission scenarios; in other words, the gamma-ray emission could be dominated by the ICS of ambient lower-energy photons by relativistic electrons. The good correlation between the gamma-ray and X-ray images is clearly presented by means of the XMM-Newton hard X-ray contours overlaid on the H.E.S.S. gamma-ray excess image (H.E.S.S. Collaboration et al. 2018). Through the deep H.E.S.S. exposure and detailed spectral and morphological studies, a significant result is that the TeV gamma-ray emission extends beyond the X-ray emission associated with the SNR shell. Therefore correlation studies of the X-ray and gamma-ray emission will play an important role in the radiation origin of RX J1713.7-3946.

To date, several theoretical models have been constructed to explain the multi-band emission from RX J1713.7-3946, such as leptonic scenarios (e.g., Liu et al. 2008; Fan et al. 2010a; Abdol et al. 2011; Li et al. 2011; Yuan et al. 2011; Ellison et al. 2012; Finke & Dermer 2012; Lee et al. 2012; Yang & Liu 2013; Zhang & Liu 2019), hadronic scenarios (e.g., Berezhko & Völk 2008, 2010; Fang et al. 2009, 2011; Inoue et al. 2012; Gabici & Aharonian 2014; Federici et al. 2015), and hybrid scenarios (involving lepton and hadron) (e.g., Zirakashvili & Aharonian 2010; Zeng et al. 2019), and some scenarios have taken nonlinear effects into account. For the sake of simplicity, the pressure of energetic particles is neglected in our calculations; we only consider the test particle approximation. Moreover, here we favor the leptonic scenario on account of the harder GeV spectrum and the good correlation between the X-ray and gamma-ray images of RX J1713.7-3946. Nevertheless, the emission origin of RX J1713.7-3946 is still debatable. As mentioned above, the diffusion process and the magnetic field strength are also uncertain in the DSA mechanism; the diffusion process is regarded as energy-dependent in some cases, such as Bohm type, Kraichnan type, and Kolmogorov type (e.g., Bhattacharjee & Sigl 2000; Burlaga et al. 2015). However, the diffusion could be also dominated by turbulent mixtures (e.g., Bykov & Toptygin 1993; Fan et al. 2010b; Zhang et al. 2017). The magnetic field strength is very complex especially in the shock downstream region, which can be simplified in many ways, such as compressional amplification (Iapichino & Bruggen 2012), amplification due to current-driven instabilities (Bell 2004), and turbulent amplification (e.g., Giacalone & Jokipii 2007; Guo et al. 2012; Ji et al. 2016; Xu & Lazarian 2016, 2017). In our model, the diffusion coefficient and the magnetic field strength will be determined by fitting the observed data. The detailed observations provide us with a great opportunity to study RX J1713.7-3946; since a good correlation has been found between the X-ray and gamma-ray images of RX J1713.7-3946, it makes sense to conduct further research on the emission scenario and radial profiles of RX J1713.7-3946.

In this paper, we apply the DSA model with the test particle approximation to research the multi-band no-thermal emission spectra and radial profiles of RX J1713.7-3946, and only investigate the leptonic scenario in studying the correlation between the X-ray and gamma-ray emissions. The structure of this paper is organized as follows: in Section 2, we describe briefly the theoretical model and carry out relevant parameter analysis; we apply the model to RX J1713.7-3946 and give the corresponding results in Section 3. We give our conclusions and a discussion in Section 4.

2. Model and Parameter Analysis

2.1. The Model

After a supernova explosion, the forward shock and reverse shock are generated by supersonically moving supernova ejecta. The forward shock propagates in the CSM, and the reverse shock propagates in the ejected gas. A numerical kinetic approach to nonlinear DSA has been developed by Zirakashvili & Aharonian (2010), and they put forward a numerical solution of the spherically symmetric hydrodynamic equations by combining the energetic particle transport and acceleration by means of the forward shock and reverse shock. It is generally assumed that some of the thermal particles are accelerated at the shock fronts and accelerated.

In the model, the gas density \( \rho(r, t) \), gas velocity \( u(r, t) \), gas pressure \( P_g(r, t) \) are described in the hydrodynamical equations, as

\[
\frac{\partial \rho}{\partial t} = - \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 u \rho) \tag{1}
\]

\[
\frac{\partial u}{\partial t} = -u \frac{\partial u}{\partial r} - \frac{1}{\rho} \left( \frac{\partial P_g}{\partial r} + \frac{\partial P}{\partial r} \right) \tag{2}
\]

\[
\frac{\partial P_g}{\partial t} = -u \frac{\partial P_g}{\partial r} - \gamma_g \rho \frac{P_g}{r^2} \frac{\partial^2 u}{\partial r^2} - (\gamma_g - 1)(w - u) \frac{\partial P}{\partial r} \tag{3}
\]
and the cosmic-ray proton momentum distribution $N(r, t, p)$ in the spherically symmetrical case is given by

$$\frac{\partial N}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} r^2 D(r, t, p) \frac{\partial N}{\partial r} - w \frac{\partial N}{\partial r} + \frac{\partial N}{\partial p} \frac{\partial p^2 b(p)}{\partial r} - \frac{1}{p^2} \frac{\partial}{\partial p} p^2 b(p) N$$

$$+ \frac{\eta_f^2 (p - p_f)}{4\pi^2 m} \rho (R_f + 0, t) (R_f - u(R_f + 0, t))$$

$$+ \frac{\eta_b^2 (p - p_b)}{4\pi^2 m} \rho (R_b - 0, t) (u(R_b - 0, t) - \dot{R}_b) \delta (r - R_b(t))$$

(4)

where $P_c = 4\pi \rho^2 dp \nu N/3$ is the cosmic-ray pressure, $w(r, t)$ is the advective velocity of cosmic rays, $\gamma_c = 5/3$ is the adiabatic index of the gas, $D(r, t, p)$ is the cosmic-ray diffusion coefficient, and $b(p) = -\partial b/\partial t$ is energy-loss rate of the particles. If the diffusive streaming of cosmic rays induces the generation of magnetohydrodynamical waves, in which the energetic particles are scattered, this will result in a difference between the cosmic ray advective velocity $w$ and the gas velocity $u$. The difference in the value of the radial component of Alfvén velocity ($V_A = B\sqrt{4\pi \rho}$) is $w = u + \xi_A V_A / p^3$ in the isotropic random magnetic field $B$ (Zirakashvili & Ptuskin 2012). The parameter $\xi_A$ represents the relative direction of fluid velocity to Alfvén velocity with $\xi_A = -1$ upstream of the forward shock and $\xi_A = 1$ upstream of the reverse shock; $\xi_A$ is zero in the other region (e.g., the downstream of the forward and reverse shocks). The last two terms in Equation (4) correspond to the injection of thermal protons with momenta $p = p_f$ and $p = p_b$, and mass $m$ at the fronts of the forward and reverse shocks at $r = R_f(t)$ and $r = R_b(t)$ respectively. The dimensionless parameters $\eta_f$ and $\eta_b$ determine the injection efficiency. Hereafter, subscripts $f$ and $b$ represent forward and reverse shock.

In our study, we only compute the contribution from energetic electrons, which are regarded as test particles, so their pressure is neglected (i.e., $P_e = 0$). In the leptonic scenario, the electrons can lose energy through processes such as synchrotron emission, ICS, bremsstrahlung emission, ionization losses, and so on. The corresponding energy-loss timescales of these processes can be expressed as $t_{\text{syn}} = 1.3 \times 10^5 (E/\text{TeV})^{-1} (B/10\mu\text{G})^{-2} \gamma^2, t_{\text{IC}} \approx t_{\text{syn}} \rho/\nu_{\text{ph}}, t_{\text{brems}} = 3.3 \times 10^5 (\rho_0/100\text{ cm}^{-3})^{-1} \gamma^{-1} \text{yr}, t_{\text{ion}} = 1.9 \times 10^4 (n_0/100\text{ cm}^{-3})^{-1} \gamma^{-1} \text{yr}$, where $E$ and $\gamma$ are the electron energy and Lorentz factor, the magnetic energy density $U_B = B^2 / 8\pi, U_{\text{ph}}$ is the energy density of the background photon field, and $n_0$ is the density of the surrounding medium (Ginzburg & Syrovatskii 1964). The synchrotron loss time of electrons with energies $\sim \text{TeV}$ is shorter with our model parameters; the synchrotron energy loss dominates over the other processes, so we consider only synchrotron energy loss with energy-loss rate $b(p) = 4\pi \rho R^2 / (9m_e^2 c^6)$ in our calculations. For simplicity, the cosmic-ray drift velocity is considered to be consistent with the gas velocity (i.e., $w = u$). The equations for the quasi-isotropic cosmic-ray momentum distribution $N(r, t, p)$ were numerically solved in the spherically symmetrical case using a finite-difference method. The radiation energy spectrum and spatial profile of the SNR are closely related to particle injection and diffusion during SNR evolution, but some problems regarding these processes are still unresolved. It seems more difficult to solve these problems for the reverse shock, so the distributions from the reverse shock are ignored in our work, i.e., particle accelerations are only considered for the forward shock. The numerical procedure for solving Equations (1)–(4) was described in detail in Zirakashvili & Ptuskin (2012).

The magnetic field plays no dynamical role in our calculation; here the evolution of magnetic field strength cannot be modeled at the shock, because no magnetohydrodynamic process is involved. The shocked ejecta and interstellar gas are separated by a contact discontinuity at $r = R_c$. For the forward shock ($r > R_f$), the magnetic field is fixed to a value of $B_0$ that can be slightly larger than the interstellar magnetic field of $\sim 3\mu\text{G}$. Downstream of the forward shock, we simply assume that the magnetic field strength satisfies the following relationship:

$$B(r, t) = \begin{cases} B_0 + \frac{B_0 - B_f}{(R_f - R_c)} (r - R_c)^\alpha, & R_c < r < R_f, \\ B_f + \frac{B_0 - B_f}{(R_f - R_f)} (r - R_f)^\alpha, & R_f < r < R_f, \\ B_0, & r > R_f \end{cases}$$

(5)

where $R_f = R_c + \xi (R_f - R_c)$ represents the position where the maximum magnetic field strength $B_m$ occurs downstream of the forward shock, and $\xi$ and $\alpha$ are two parameters that determine the distribution of the magnetic field. $B_f$ and $B_0$ are magnetic field strength upstream of the forward shock and at the shock front (at $r = R_f$) respectively. Although we do not consider the contribution of the reverse shock, its magnetic field strength could also exist as considered by Zirakashvili & Ptuskin (2012); here we simply set $B = 3\mu\text{G}$ within the reverse shock.

We take into account energy-dependent diffusion, on the basis of multi-band observation data, and further judge whether or not the diffusion coefficient is strongly related to energy. The diffusion coefficients, which depend on the energy of cosmic-ray particles, can be expressed as

$$D(E) = 10^{28} \chi \left( \frac{E}{10\text{ GeV}} \right)^{\delta}$$

(6)

where $E$ is the accelerated particle energy, $\chi$ is the correction factor, and $\delta$ is an index which depends on the turbulence spectrum of the magnetic field; $\delta = 0.0$ for energy-independent diffusion, $\delta = 1/3$ for Kolmogorov type, $\delta = 1/2$ for Kraichnan type, and $\delta = 1$ for Bohm type (e.g., Berezinskii et al. 1990; Bhattacharjee & Sigl 2000; Fujita et al. 2009).
Based on the DSA model, the hydrodynamic and particle propagation equations are solved by means of combining the distribution of magnetic field strength and energy-dependent diffusion. Subsequently, the spectra of accelerated particles and photon spectra during the whole evolution of RX J1713.7-3946 can be produced. After the projection effect is taken into account, we further calculate the radial profiles of the brightness distributions of the X-ray and gamma-ray emission from RX J1713.7-3946. The photon emission from radio to X-ray bands are dominated by synchrotron emission from accelerated electrons; the GeV–TeV gamma-rays are produced by ICS of high-energy electrons. For the calculation of radiation, one can refer to some related formulas (e.g., Blumenthal & Gould 1970; Rybicki & Lightman 1979; Zhang & Fang 2007).

### 2.2. Parameter Analysis

In this section, we apply the model to RX J1713.7-3946, and some appropriate parameters will be chosen to fit the multiband photon emission spectrum and radial radiation profile. From existing theories and observations as described in Section 1, the age of RX J1713.7-3946 is fixed at $t_{\text{age}} = 1625$ yr, and its distance $d$ is equal to 1 kpc. After the supernova explosion, the ejecta is thought to have a velocity distribution (Zirakashvili & Ptuskin 2012)

$$P(V) = \frac{3(k - 3)}{4\pi k} \begin{cases} 1, & V < V_{ej} \\ (V/V_{ej})^{-k}, & V > V_{ej} \end{cases}$$

The characteristic ejecta velocity is

$$V_{ej} = \sqrt{\frac{10(k - 5)E_{in}}{3(k - 3)M_{ej}}}$$

where we set the energy of the supernova explosion as $E_{in} = 1.0 \times 10^{51}$ erg and the ejecta mass $M_{ej} = 2 M_\odot$; $k = 9$ is the power-law index of this distribution accounting for possible supernova type Ib/c and IIb. For the sake of simplicity, the surrounding medium density $n_0$ is assumed to be uniform, and its value is selected according to the position of the shock front considering different radial profiles of X-ray and gamma-ray radiation. In our work, the two brighter regions (i.e., Region 3 and Region 4 in H.E.S.S. Collaboration et al. 2018) in both X-ray and gamma-ray bands are singled out as typical cases; we also refer to them as “Case 1” and “Case 2” respectively in the following sections.

The problem of electron injection is still barely understood in diffusion shock acceleration theory in SNRs. A rather high injection energy of electrons 100 MeV is assumed for suprathermal electron injection. As discussed in Zirakashvili & Ptuskin (2012), the electron injection efficiency $\eta'$ at the forward shock is probably relative to the photoionization of accelerated ions, and $\eta' \propto R_T^2 / e^2$. In what follows, the accelerated electrons are considered as test particles (the electrons are energetically unimportant), and to reproduce the radio fluxes of RX J1713.7-3946, we assume that electrons are injected at the forward shock with a high injection energy of $p_e = 100$ MeV and a low efficiency of $\eta' = 10^{-7} R_T^2 / c^2$, taken to be independent of the shock velocity; $c$ is the velocity of light. Subsequently, particle diffusion is formulated with the above-mentioned four values of $\delta$ by combining with the observation data. Here, with $B_f = B_0 = 6 \mu$G, $B_m = 45 \mu$G, $\alpha = 4$, and $\xi = 0.4$ fixed, we calculate the photon emission spectra of RX J1713.7-3946 shown in Figure 1. From the figure, the emission of radio to X-ray bands and gamma-ray emission are respectively from synchrotron radiation and ICS of relativistic electrons; the background photon field of ICS is composed of cosmic microwave background radiation with a temperature of 2.7 K and an energy density of 0.26 eV cm$^{-3}$, and an interstellar infrared radiation field at 30 K and 0.3 eV cm$^{-3}$ (e.g., Porter et al. 2006; Finke & Dermer 2012). As shown in Figure 1, if the diffusion is energy-independent, i.e., the index $\delta = 0.0$, it seems impossible to fit the multi-band photon emission spectrum in this situation. As a consequence, the energy-dependent diffusion should be a better choice for fitting the photon emission spectra, especially at $\delta = 1/3$, therefore we always adopt $\delta = 1/3$ in following calculations.

In general, the non-thermal X-ray emission is mainly from the synchrotron radiation of high-energy electrons, and the X-ray radiation intensity is proportional to the magnetic field strength. Given the effect of the magnetic field on the radial radiation profile in the X-ray band, we calculate the radial profiles of RX J1713.7-3946 in the X-ray and gamma-ray bands by selecting different parameters $\alpha$ and $\xi$. In Figure 2 we provide different distributions of magnetic field strength, and calculate the corresponding radial profiles for Case 1. The gamma-ray radial profile is almost impervious to the distribution change, which does not depend on the magnetic field strength because of the different radiation mechanism. It is obvious that the result for $\alpha = 4.0$ and $\xi = 0.4$ is consistent with the observed X-ray radial profile for this case, although there are still some differences in some regions, such as the innermost region and the peak position; more detailed analysis will be carried out in the following sections. It can be seen roughly from Figure 2 that $\alpha$ mainly determines the profile shape in the radius range from 0’3 to 0’5, while the peak position of the profile is affected by $\xi$, which is a crucial factor in fitting the observation in the region with radius <0’4.
Compared to Case 1, the gamma-ray emission extending beyond the X-ray-emitting shell is slightly less obvious in Case 2 where we also adjust the ambient density from $0.45 \text{ cm}^{-3}$ for the case 1 to $0.2 \text{ cm}^{-3}$ to fit the location of the brightness peak. The X-ray surface brightness drops more slowly with position from the peak to the forward shock front in this case, so the distribution of magnetic field strength should be different from the result of Case 1, and the value of $\alpha$ should be smaller. Now we set $\xi = 0.0$ and $\alpha = 1.0$ for a magnetic field strength changing linearly with position; $B_f = 6 \mu G$, $B_f = 6$, 10, 12 $\mu G$ are adopted by considering different compression amplifications at the forward shock front, and $B_m = 27 \mu G$ is chosen to

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Distributions of magnetic field strength and radial profile in Case 1. Left panel: distribution of the magnetic field strength varying with radius; $\xi = 0.4$ fixed with $\alpha = 1.0, 2.0, 4.0$ (upper), and $\alpha = 4.0$ fixed with $\xi = 0.0, 0.2, 0.4$ (lower). Right panel: radial profiles of RX J1713.7-3946 varying with radius corresponding to the left figure in Case 1; the X-ray profile with energy $1–10$ keV (red dotted line) is extracted from the XMM-Newton map, gamma-ray profile above 250 GeV (black crosses) is from the H.E.S.S. maps, and the same convolution is processed with 0.048 (H.E.S.S. Collaboration et al. 2018). Theoretical calculation results are shown as the dashed lines (gamma-ray profiles) and solid lines (X-ray profiles) in the right panel.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Distributions of magnetic field strength and radial profiles in Case 2. Left panel: distribution of magnetic field strength varying with radius; $\alpha = 1.0$ and $\xi = 0.0$ fixed with $B_f = 6.0, 10, 12 \mu G$. Right panel: radial profiles of RX J1713.7-3946 varying with radius corresponding to the left panel; the descriptions of experimental data and theoretical calculation results are as in Figure 2, but for different regions.
fit the multi-band emission spectra of RX J1713.7-3946. The results are shown in Figure 3, where it is observed that \( B_f = 10 \mu G \) is appropriate to fit the radial profile in Case 2; in other words, compressional amplification of magnetic field strength is likely to exist at the shock front.

### 3. Results of Modeling RX J1713.7-3946

On the basis of the parameter analysis in Section 2.2, we select some appropriate model parameters, and further analyze the shock evolution, magnetic field distributions, multi-band energy spectra and radial profiles of RX J1713.7-3946 for the aforementioned two cases. As previously discussed, here we will take an energy-dependent diffusion with index \( \delta = 1/3 \) and a position-dependent magnetic field; the parameters \( E_{\text{min}}, M_{\text{ej}}, k, p_{\text{s}}, \eta^1, \eta^2, \delta, \) and \( B_0 \) are fixed to those values determined in Section 2.2 for both cases, while the parameters \( n_0, \chi, \) and the other parameters \( (B_f, B_{m\perp}, \alpha, \xi, \) and \( \zeta \) that are used to describe the magnetic field strength are discrepant in the different cases, as listed in Table 1.

In this section, we apply the model to explore the radial dependences of RX J1713.7-3946 with gas characteristics and magnetic field strength, and further study the multi-band nonthermal emission and surface brightness distribution for this remnant. For the two cases, with age \( t_{\text{age}} = 1625 \) yr of the remnant, we can inversely derive the surrounding medium density \( n_0 \) via the observed brightness distributions after setting initial and boundary conditions. From Table 1, the parameters associated with the magnetic field strength are determined by the shape of the radial profiles of the X-ray emission. Although the maximum value of the magnetic field strength is different for the two cases, their average values are close, which should be confirmed by the observed X-ray to gamma-ray energy flux ratio when the gamma emission of RX J1713.7-3946 is from ICS of relativistic electrons. In Figures 4 and 5, the positions of the contact discontinuity (between the ejecta and the interstellar gas), the forward and reverse shocks can be seen in the upper left panel; their radii are respectively located at \( R_c = 5.0 \) pc, \( R_f = 7.2 \) pc, and \( R_b = 3.38 \) pc for Case 1, while \( R_c = 6.14 \) pc, \( R_f = 8.25 \) pc and \( R_b = 4.86 \) pc for Case 2. \( R_f = 7.2 \) pc for Case 1 is close to the result of \( ~7 \) pc that was given by the model fit in Zhang & Chen (2016). The speed of the forward shock \( V_f \) is equal to 2170 km s\(^{-1}\) and 2630 km s\(^{-1}\) for Case 1 and Case 2 respectively; these are much lower than the upper limit of the shock speed, 4500 km s\(^{-1}\) (Uchiyama et al. 2007). Recently, the shock wave speed at the northwestern shell was measured to be 3900 ± 300 km s\(^{-1}\) with an estimated distance of \( d = 1 \) kpc (Tsuji & Uchiyama 2016). Tanaka et al. (2020) also gave measured velocities of 3800 ± 100 km s\(^{-1}\) and 2300 ± 200 km s\(^{-1}\) for two different X-ray bright blobs at the western edge of the shell.

For multiband emission spectra of RX J1713.7-3946 in the upper right panel of Figures 4 and 5, the emissions from radio to X-ray bands are contributed by the synchrotron emission of relativistic electrons; the GeV–TeV gamma-ray emissions are from ICS of these electrons on the background photon fields, although the fitted results are not perfect. It is obvious that the contribution from downstream of the forward shock is dominant over the total emissions, while the hard X-ray and TeV gamma-ray emissions could be partly from the shock upstream. The structure of the magnetic field in the shock downstream is closely related to the X-ray radiation profile. Xu & Lazarian (2016) investigated the magnetic field amplification in the context of fully ionized and weakly ionized gas, and found that the nonlinear dynamo in fully ionized gas can lead to a linear-in-time growth of magnetic energy by means of turbulent magnetic diffusion (i.e., the growth of the magnetic field is nonlinear with time), while the dynamo is characterized by a linear-in-time growth of the magnetic field in a weakly ionized medium. In our calculations, for the sake of fitting the observed data, the growth of magnetic field strength is simply assumed to be nonlinear and linear with position for Case 1 and Case 2 respectively in shock downstream; a possible compression amplification at the shock front is also taken into account to better fit the observations in Case 2.

From the lower right panel we can see that radial profiles with energy above 250 GeV are well consistent with the corresponding experimental data around the peak position of surface brightness for the two cases, but there are still differences in the innermost regions with radius \( r < 0.2 \) pc and outermost regions \( r > 0.4 \) for Case 1, \( r < 0.5 \) for Case 2. The theoretical values are on the high side in the innermost regions; in contrast, theoretical values are on the low side in the outermost regions. In both cases, radial profiles with energy above 1–10 keV are in good agreement with the experimental data outside the peak position, but theoretical values are significantly higher than the observed values inside the peak position. Certainly, these biases are understandable because of the spherically symmetric hypothesis in our theoretical model. As a matter of fact, the local physical environment could be very complex, such as an anisotropic surrounding medium density, partially or fully ionized local gas, and so on. In the case of non-spherical symmetry, theoretical results in the outer layer of the remnant should be closer to our spherically symmetric results on account of the local projection effect, therefore this is reasonable to explain the X-ray radial profiles. The gamma-ray emission extending beyond the X-ray-emitting shell is not obvious in our results, especially in the outer regions where gamma-ray emission could be provided by the highest-energy particles that escaped from the shock via interacting with the surrounding medium (e.g., Li & Chen 2010, 2012; Ohira et al. 2011, 2012; Yang et al. 2015b; Zhang & Chen 2016).

### 4. Summary and Discussion

We use the DSA model with the test particle approximation, and considering energy-dependent diffusion and position-dependent magnetic field strength, to investigate the multi-band photon emission spectra and the radial surface brightness distributions of RX J1713.7-3946 in the leptonic scenario for gamma-ray emission. Here we have ignored the contribution from the reverse shock because of its greater uncertainty. After selecting the appropriate parameters, the equations for hydrodynamic and particle propagation were solved, and then we explored the dynamic evolution of RX J1713.7-3946 and obtained the electron momentum distributions, photon emission spectra, and radial profiles in two different zones. In the
calculation, we have assumed spherical symmetry for simplicity, but for real SNRs there should be a different mean density in different regions. The diffusion coefficients and magnetic field strength are critical to the results; the former were assumed to be energy-dependent with our spectral fit given the index $\delta = 1/3$. For Case 1, the magnetic field strength increased nonlinearly away from the shock front in the downstream region and achieved the maximum value before reaching the contact discontinuity by possible turbulent amplification, then decreased nonlinearly. For Case 2, it was postulated that there was a compression amplification of the magnetic field strength at the shock front, which then increased linearly up to the contact discontinuity. Some detailed theory about magnetic field amplification has also been discussed by many authors (e.g., Bell 2004; Giacalone & Jokipii 2007; Iapichino & Bruggen 2012; Guo et al. 2012; Ji et al. 2016; Xu & Lazarian 2012, 2017). Here we have only given some results from the perspective of fitting observations with simple assumptions; further detailed theoretical studies will be necessary for real SNR environments, which are beyond the scope of this paper.

The multi-band photon spectra were reproduced by synchrotron radiation and ICS from relativistic electrons, but the origin of gamma-ray emission from RX J1713.7-3946 is still an open problem. In particular, our model underestimates the gamma-ray brightness just ahead of the X-ray shell while it overproduces X-ray and gamma-ray emission in the central region. Zhang & Chen (2016) posited that the gamma-ray emission could be from ICS of relativistic electrons, the interaction between the trapped energetic protons and the shocked clumps inside the SNR, or from the diffusive protons that escaped from the shock, and they believed that the extended gamma-ray emission should be from hadronic components in the outer emitting region. The very hard energy spectrum at low energies could be also from hadronic processes if the remnant was expanding inside a clumpy medium (e.g., Inoue et al. 2012; Gabici & Aharonian 2014; Celli et al. 2019). Based on the steady state or time-dependent nonlinear DSA model, the hydrodynamic process and the multi-band photon spectra of RX J1713.7-3946 have been studied (e.g., Ellison et al. 2010, 2012; Zirakashvili & Aharonian 2010; Yasuda & Lee 2019). In particular, considering both hadronic and leptonic scenarios, Zirakashvili & Aharonian (2010) discussed the radial profiles of brightness distributions of X-ray, gamma-ray, and radio emission, and fitted an azimuthally averaged TeV gamma-ray radial profile detected by the H.E.S.S. Yang et al. (2015a) also studied the azimuthally averaged TeV gamma-ray radial profile of RX J1713.7-3946 using 2D...
magnetohydrodynamic simulations in the leptonic scenario; in their opinion, a lower surrounding medium density could lead to a sharper drop of the TeV brightness near the outer emitting region, and a relatively good fit was presented with a surrounding medium density $n_0 = 0.8 \, \text{cm}^{-3}$, which is even larger than the values used in our model. Using the newer observation data (those in Case 1), Ohira & Yamazaki (2017) explained the broken power-law spectrum of GeV–TeV gamma-rays as due to ICS and believed that the extended component of the gamma-ray profile should be from a cosmic-ray precursor of accelerated electrons. They assumed that the magnetic field strength was constant, and that the diffusion coefficient around the shock front had a radial dependence and was spatially constant in the shock upstream region, but the gamma-ray profile in the inner region and the observed X-ray profile cannot be well described in their model. Recently, Acero et al. (2019) indicated that the correlation between the X-ray emission and gamma-rays is nonlinear with an approximate flux $F_\gamma \propto \sqrt{F_X}$, and they did not confirm that the gamma-ray emission extends further than the X-ray emission.

In short, there are still some difficulties in explaining the origin of multi-band emission and radial profiles of surface brightness for RX J1713.7-946. Future observations with higher sensitivity and angular resolution will be valuable. The morphological and spectral properties of several other SNRs have also been detected, such as RX J0852-622, RCW 86, and HESS J1731-347; the non-thermal radiation characteristics from these remnants are very similar to those of RX J1713.7-3946. Future observations with higher sensitivity and angular resolution, such as with the Cerenkov Telescope Array (CTA Consortium et al. 2019) and the Large High Altitude Air Shower Observatory (Bai et al. 2019) experiments, will provide us with more detailed information about gamma-ray emission from SNRs, and help us to understand the particle acceleration mechanism and distinguish whether the extended component of the gamma-ray profile is from the shock precursor or escaping cosmic rays.

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