



Emissions from supernova remnants in the presence of small-scale random magnetic fields

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Abstract: We study non-thermal emissions by relativistic electrons from supernova remnants (SNRs) in the presence of small-scale random magnetic fields. We construct jitter and inverse Compton emission models. We apply them to the multi-wavelength data of TeV gamma-ray sources SNRs RX J1713.7-3946 (G347.3-0.5) and RX J0852.0-4622 (G266.6-1.2). The physical fit parameters of magnetic fields are discussed.

Introduction

The origin of the TeV gamma-ray emissions from the prominent shell-type supernova remnants (SNRs) RX J1713.7-3946 [1], [2], [3], [4] and RX J0852.0-4622 [5], [6], [7] is the current issues. Two possible origins of TeV gamma-ray emissions are proposed: neutral pion decay gamma-rays from inelastic interaction of relativistic protons with ambient matter, and inverse Compton (IC) scattering of the cosmic microwave background (CMB) and other target soft photons by relativistic electrons. On the assumption that synchrotron (in radio and X-ray energy regions) and IC (in TeV region) emissions are produced by the same electrons, the magnetic fields strength must be less than several μG for the explanation of the observed TeV gamma-ray flux. If the value of the magnetic field strength at the particle acceleration site is expected to be larger than that of the interstellar medium, the IC origin is not favored. Through multiband approach and modeling based on a nonlinear kinetic theory [8], the proton scenario is found to be more favorable. However, we have not yet reached any firm conclusion that these SNRs are the cosmic-ray acceleration sites, because we do not know key parameters like the magnetic field strength and the electron to proton ratio, which is difficult to measure directly.

Within the framework of one-zone synchrotron plus IC emission models, there exists the difficulty of fitting multiband data. This difficulty is avoidable if an additional parameter, the magnetic field filling factor f_B [9], [10] are introduced. As the result of fitting, very small filling factors $f_B = 0.1 \sim 1\%$ are obtained: the emissions originate from two regions, the synchrotron emission from very small confined regions with the magnetic fields of orders of 10 to 100 μG , and the IC one from the rest of the region with much lower magnetic field. Although this two-zone model is based on the picture that the magnetic fields amplified by the turbulence in SNRs become very patchy, there is no physical justification for the values of the magnetic filling factor and strength.

Recent H.E.S.S. morphological study of the SNR RX J1713.7-3946 has shown that there is a striking correlation between the X-ray and the TeV gamma-ray image [4]. A simple explanation for this correlation is not easy to be found in the two-zone leptonic models. On the other hand, the hadronic scenario is promising, but it is not yet clear whether this model may give us a natural explanation for the correlation. In this paper, we present an alternative possible explanation, constructing jitter [11], [12], [13], [14] and IC emission model for these SNRs and determining the physical parameters of relativistic electrons and magnetic fields. One crucial and underlying physical process in particle ac-

celeration is magnetic fields generation. The jitter radiation model suggests that we can test the mechanism of magnetic fields generation. And this model implies that the correlation between the X-ray and the TeV gamma-ray distributions might be explained naturally because the jitter and IC emissions are produced by the same population of electrons.

Emission Model

Jitter radiation

We consider photon emissions produced by relativistic electrons with Lorentz factor γ scattered on small-scale random magnetic fields. The spectrum depends on the relation between the deflection angle of the electron α and the beaming angle of the emission $\Delta\theta \sim 1/\gamma$ [12]. The deflection-to-beaming ratio is defined as follows:

$$\delta = \frac{\gamma}{k_B r_L} \sim \frac{\gamma \lambda_B}{r_L} \sim \frac{e B_\perp \lambda_B}{m_e c^2} \sim \frac{\alpha}{\Delta\theta}, \quad (1)$$

where λ_B is a typical correlation scale of random magnetic fields, k_B the wavenumber, r_L the Larmor radius of the electron, B_\perp the strength of the magnetic field perpendicular to the electron velocity vector, e and m_e the electron charge and mass, and c the speed of light. Note that this ratio is independent of the electron energy γ and dependent on only B_\perp and k_B .

When $\delta \gg 1$, an observer sees emissions from short parts of the electron trajectory, which parts are almost parallel to the line of sight. This case is like pure synchrotron radiation from large-scale magnetic fields with slight non-uniformity. When $\delta \ll 1$, emissions from the entire trajectory are observed. In this case, the electron runs almost straight along the line of sight and is scattered perpendicularly as a result of the small-scale random magnetic fields. We call this emissions ‘‘jitter’’ radiations. In a real case, magnetic fields are expected to be a mixture of different scales. Then, the resultant spectra are obtainable by considering emissions from different-scale magnetic field [12]. However, for simplicity, in the present work we will focus our attention on pure jitter radiation.

The jitter radiation spectral power emitted by a single electron is given by

$$P(\omega) = r_e^2 \frac{\langle B^2 \rangle}{2k_B} J\left(\frac{\omega}{\omega_j}, \phi\right), \quad (2)$$

where $r_e = e^2/m_e c^2$ is the classical electron radius, ω_j is the characteristic frequency of the jitter radiation $\omega_j = \gamma^2 k_B c$, which is independent of the magnetic field strength, ϕ is the angle between the normal to the shock and the electron velocity, and $\langle B^2 \rangle$ is the mean square of the small-scale random magnetic fields.

Radiation spectra

We assume that the total number spectrum of electrons at the source follows a power law with index p and an exponential energy cutoff $\gamma_{max} = E_{max}/m_e c^2$, where E_{max} is the maximum energy of the electrons:

$$N_e(\gamma) = N_{e0} \gamma^{-p} \exp(-\gamma/\gamma_{max}), \quad (3)$$

where N_{e0} is a normalization factor. The flux of jitter radiation can be calculated by

$$f(\omega) = \frac{1}{4\pi d^2} \int \langle P(\omega) \rangle N_e(\gamma) d\gamma, \quad (4)$$

where d is the distance to the source and $\langle P(\omega) \rangle$ is the angle-averaged jitter radiation spectral power.

We have the following three fitting parameters for the jitter radiation:

$$\begin{aligned} s &= \frac{N_{e0}}{4\pi d^2} k_B^u \langle B^2 \rangle, \\ t &= \sqrt{k_B} E_{max}, \\ u &= \frac{p-3}{2}, \end{aligned}$$

the values of which parameters can be determined by fitting observed radio and X-ray data. The parameter s is essentially a normalization factor. The parameter t governs the cutoff energy of the jitter radiation spectrum. The larger value of t means the higher energy cutoff of the radiation. The parameter $-u$ is the spectral index of the differential flux (multiplied by the squared energy of the photon) in energy below the cutoff.

We assume that the observed TeV gamma rays come from the IC scattering of the CMB radiation, by the same relativistic electrons which produce

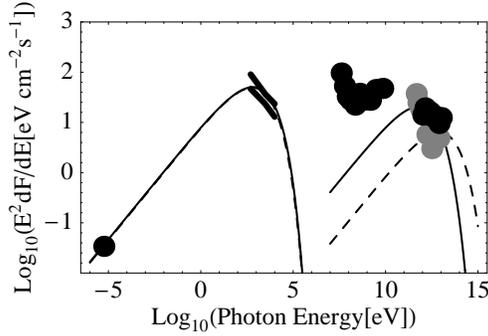


Figure 1: Multiband spectrum of RX J1713.7-3946. The observed flux from radio to TeV gamma-ray band, except for the EGRET upper limits, are indicated by the black circles and thick solid lines for the X-ray band. In the TeV region, the black circles denote H.E.S.S. data and gray circles CANGAROO one.

jitter radiation. By fitting observed TeV gamma-ray flux, we can determine the two parameters $N_{e0}/4\pi d^2$ and E_{max} , assuming the value of the electron spectrum index p . The expected value of p (or u) is determined by the EGRET upper limit and the observed radio spectral index. And then, from the values of s and t determined as fitting observed radio and X-ray data, the physical parameters of random magnetic fields k_B and $\langle B^2 \rangle$ are obtained.

Results

We show the multiband spectra of the SNRs RX J1713.7-3946(G347.3-0.5) and RX J0852.0-4622(G266.6-1.2) in Figure 1 and 2, where the solid lines represent the fitting results of the data with pure jitter plus IC emission models. In Table 1, the resultant fit parameters for the two SNRs are listed. We can fit the multiband data of both SNRs by pure jitter plus IC emission models, determining the values of the parameters p , E_{max} , and $N_{e0}/4\pi d^2$ for the electron energy distribution and k_B and $\langle B^2 \rangle$ for random magnetic fields.

In Figure 1 and 2, the fitting results of synchrotron emission models are denoted by the dashed lines, although only the solid lines of the jitter radiation are seen since the lines of jitter and synchrotron

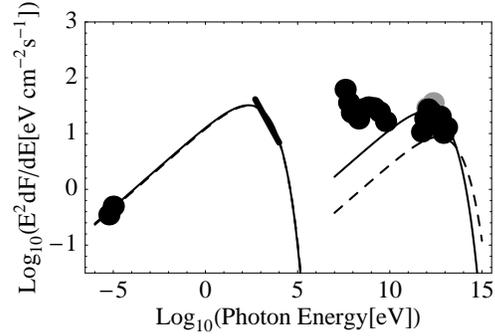


Figure 2: Multiband spectrum of RX J0852.0-4622. This is the same plot as in Figure 1.

radiation overlap. IC emissions by the same electrons which produce synchrotron emissions, are shown by the dashed lines. These lines demonstrate that one-zone synchrotron plus IC emission models cannot fit data for both SNRs.

The one-zone synchrotron plus IC model has only four adjusting parameters p , E_{max} , $N_{e0}/4\pi d^2$, and B . On the other hand, the pure jitter plus IC emission model has five parameters. With one additional freedom k_B in the latter model, the multiband data can be fitted. It is noticeable that this parameter k_B determines the characteristic frequency of the jitter radiation ω_j , and is independent of the magnetic field strength. The value of k_B can be determined from the values of $t = \sqrt{k_B} E_{max}$, related to the energy cutoff of the jitter radiation, and E_{max} , related to that of the IC one. Then, the value of $\langle B^2 \rangle$ is determined from $s = (N_{e0}/4\pi d^2) k_B^u \langle B^2 \rangle$, related to flux level of the jitter radiation, $N_{e0}/4\pi d^2$, related to that of the IC one, p (or u), and k_B . The five parameters of the pure jitter plus IC emission model can be completely determined fitting the multiband data.

We can fit the multi-wavelength data of two prominent TeV shell-type SNRs RX J1713.7-3946 and RX J0852.0-4622 by pure jitter and IC emission models with several tens of μG strength and the order of $\sim 10^7$ cm correlation length of random magnetic field, as shown in Table 1.

parameters	RX J1713.7	RX J0852.0
p	2.1	2.42
E_{max} (TeV)	12	25
k_B (cm $^{-1}$)	9.0×10^{-8}	1.7×10^{-8}
$\sqrt{\langle B^2 \rangle}$ (μ G)	48	34
δ	0.31	1.2
W_e (erg)	1.1×10^{48}	2.4×10^{47}

Table 1: The fitting parameters for the two SNRs. W_e is the total electron energy, calculated using the values of $N_{e0}/4\pi d^2$ and assuming a source distance d of 1 kpc for RX J1713.7-3946 and 0.2 kpc for RX J0852.0-4622, respectively.

Discussions

We discuss these properties of random magnetic fields in collisionless shock of SNRs. Recently Medvedev et al. [15] show the magnetic fields can be generated by collisionless shocks in clusters of galaxies. Here we apply their results for non-relativistic shocks to the case of SNRs. As a strong shock expands into the ambient medium, bulk velocities of electrons and protons are comparable to the shock velocity v_{sh} . Then, the magnetic field generated by protons becomes dominant because the energy budget of protons is larger. The wavelength of the fastest growing mode, which determines a correlation scale of the magnetic field, is $\lambda_B \sim 2\pi c/\omega_{pp}$:

$$\lambda_B \sim 1.4 \times 10^8 \text{ cm} \left(\frac{n_p}{1 \text{ cm}^{-3}} \right)^{-1/2},$$

where $\omega_{pp} = (4\pi e^2 n_p / m_p)^{1/2}$ is the proton plasma frequency, m_p the proton mass, and n_p the proton number density in the ambient medium. The amplification of the magnetic field stops when protons are confined in the field. This saturation occurs when the Larmor radius of the proton becomes comparable to the correlation scale of the magnetic field: $r_{Lp} \sim v_{th}/\omega_{cp} \sim \lambda_B$, where v_{th} is the proton thermal velocity $\sim v_{sh}$ and $\omega_{cp} = eB/m_p c$ is proton-cyclotron frequency. The saturation value of the magnetic field is given by

$$B \sim 73 \mu\text{G} \left(\frac{v_{sh}}{10^3 \text{ km/s}} \right) \left(\frac{n_p}{1 \text{ cm}^{-3}} \right)^{1/2}.$$

The necessary properties of random magnetic fields for a pure jitter and IC emission model may be produced.

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