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X-ray synchrotron emission from 10–100 TeV cosmic-ray electrons in the supernova remnant SN 1006

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1 Introduction

The search for evidence of the origin of Galactic cosmic rays has been an active area of research for many decades. While little evidence exists about the sites where very–high-energy nuclei are accelerated, the results of recent X-ray and gamma-ray observations indicate that at least some of the cosmic-ray electrons are accelerated in the shocks of supernova remnants (Koyama et al. (1995); Koyama et al. (1997); Allen et al. (1997); Tanimori et al. (1998); Allen et al. (1999); Vink et al. (1999); Slane et al. (1999); Muraishi et al. (2000); Borkowski et al. (2000); Dyer et al. (2001); Allen et al. (2001)). SN 1006 is one remnant for which there is evidence that cosmic-ray electrons have been accelerated to energies as high as about 100 TeV (Koyama et al. (1995); Tanimori et al. (1998); Allen et al. (2001)). In this paper, measurements of the X-ray and radio emission of the remnant are used to determine the parameters of the non-thermal electron spectrum. Although there is no evidence to indicate that cosmic-ray nuclei are accelerated in SN 1006, relativistic electrons and nuclei are expected to be accelerated in a similar manner (Ellison and Reynolds (1991)). Therefore, we estimate the parameters of the proton and helium spectra of the remnant. The results of this analysis show that the remnant is a significant source of Galactic cosmic rays (at least cosmic-ray electrons) and provide some support for the idea that Galactic cosmic rays are accelerated predominantly in the shocks of supernova remnants.

2 Data and Analysis

To accurately model the shape of the entire X-ray spectrum of SN 1006, from 0.12–17 keV, we analyzed data obtained using the Proportional Counter Array (PCA) of the *Rossi X-Ray Timing Explorer* (*RXTE*) satellite, the Solid-state Imaging Spectrometers (SISs) of the *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*), and the Position Sensitive Proportional Counter (PSPC) of the *Röntgen* satellite (*ROSAT*). A joint fit to the *RXTE* PCA, *ASCA* SIS, and *ROSAT* PSPC data was performed using several sets of thermal and non-thermal X-ray emission models. The model that fit the data best includes a non-equilibrium–ionization component ($kT_{\rm e} = 0.58^{+0.02}_{-0.27}$ keV and $n_0 t = 9^{+12}_{-1} \times 10^9$ cm^{-3} s) to describe the thermal emission and a broken–power-law component ($\Gamma_1 = 2.08 \pm 0.14$, $\Gamma_2 = 3.02 \pm 0.17$, and $E_{\rm break} = 1.85 \pm 0.20$ keV) to describe the non-thermal emission. A broken power-law model is used here to approximate a gradually steepening non-thermal X-ray spectrum. Such a spectrum is expected if the non-thermal emission is produced by synchrotron radiation (Reynolds (1996)). A significant non-thermal spectral steepening is required, since the difference between the high-energy and low-energy photon indices of the broken power-law ≥ 0.7 at the 3 σ confidence level (Allen et al. (2001)), The value of the break energy of the broken power-law is not physically meaningful. It does not correspond to a feature in the non-thermal X-ray spectrum of SN 1006. The value of this parameter is determined by the transition from the relatively high count-rate portion of the *ROSAT* PSPC spectrum to the relatively high count-rate portion of the *RXTE* PCA spectrum. The data and best-fit model are shown in figures 1–3. In general, the model fits the 0.12–17 keV data quite well.

3 Discussion and Conclusions

Reynolds (1996) argues convincingly that the only plausible explanation of the emission is synchrotron radiation from electrons accelerated to energies of about 10–100 TeV. This conclusion is supported by the results of the present analysis, which show that the non-thermal spectrum steepens with increasing energy. Figure 4 illustrates the key elements of Reynolds arguments. This figure displays a compilation of the broad-band spectral data of SN 1006 and estimates of the flux of various photon emission processes. As shown, the non-thermal X-ray spectrum is consistent with a model

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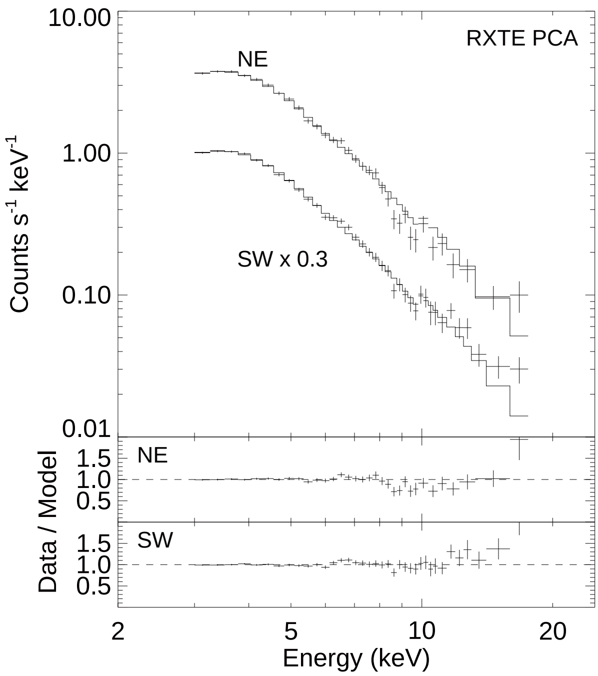

Fig. 1. The *RXTE* PCA data of SN 1006. The top panel includes data for pointings at the the north-eastern (NE) and south-western (SW) rims of the remnant. The entire remnant is in the field-of-view of the PCA at both pointing positions. The histograms through the data are the results of the best-fit model. The spectral data and model of the south-western pointing have been multiplied by a factor of 0.3 for clarity. The lower panels show the ratios of the data to the model for both pointings. See Allen et al. (2001) for details.

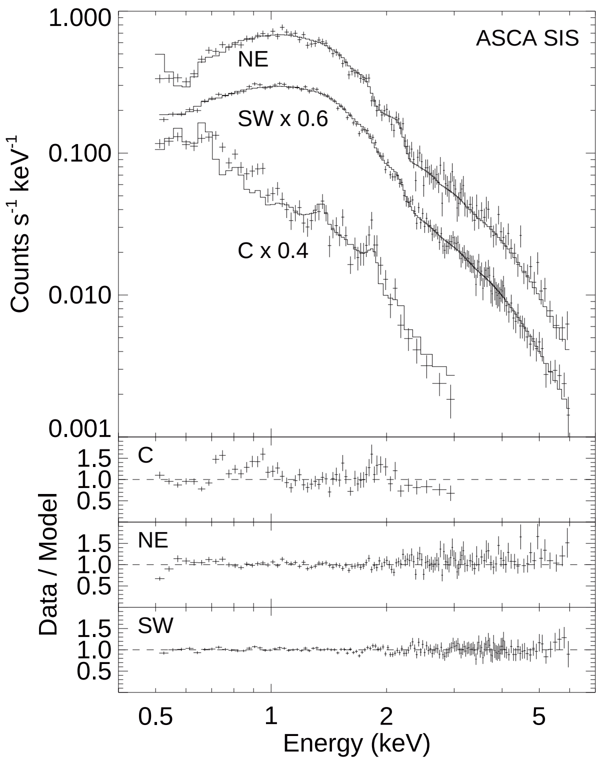

Fig. 2. The *ASCA* SIS data for spatially-separate north-eastern (NE), south-western (SW), and central (C) regions of SN 1006. Refer to the caption of fig. 1.

of synchrotron radiation, but it is not consistent with models of non-thermal bremsstrahlung or inverse Compton scattering. The TeV gamma-ray data can be described by inverse Compton scattering.

The available radio and X-ray data of SN 1006 can be used to infer the parameters of the spectrum of the cosmic-ray electrons producing the synchrotron emission. For simplicity, the relativistic electron spectrum is assumed to have the form $dn_{\rm e}/dE = A_{\rm e}E^{-\Gamma_{\rm e}}e^{-E/\epsilon_{\rm e}}$. This form is the high-energy limit of Bell's (1978) expression:

$$dn/dE = A(E+mc^2)(E^2+2mc^2E)^{-(\Gamma+1)/2}e^{-E/\epsilon}, \quad (1)$$

where $E\ (=(\gamma-1)mc^2)$ is the kinetic energy of the particles and the exponential cutoff is added to the formula of Bell. The electron spectral index $\Gamma_{\rm e}$ can be determined from the spectral index of the radio data: $\Gamma_{\rm e} = 2\alpha + 1 = 2.14 \pm 0.12$ (Allen et al. (2001)). However, estimates of the normalization factor $A_{\rm e}$ and the exponential cut-off energy $\epsilon_{\rm e}$ of the electrons can not be uniquely determined from the synchrotron data alone because the normalization ($S_\nu \propto A_{\rm e}B^{1+\alpha}$) and the roll-off energy ($E_{\rm roll} \propto \epsilon_{\rm e}^2 B$) of the synchrotron spectrum depend on the strength of the magnetic field. (Note that $E_{\rm roll} = 0.1$ keV in figure 4.) Since the normalization of the inverse-Compton spectrum produced by the relativistic electrons depends on $A_{\rm e}$ (and the known spectrum of the cosmic microwave background radiation), but not B, the TeV gamma-ray data can be used to determine $A_{\rm e}$. Then the flux and the roll-off energy of the synchrotron spectrum can be used to determine B and $\epsilon_{\rm e}$, respectively. For example, if the cosmic-ray electrons and the magnetic field of SN 1006 have effective volume-filling factors $f_{\rm e} = f_B = 0.25$, if the volume of the remnant $V = \frac{4}{3}\pi\theta^3 d^3 = 5 \times 10^{58}$ cm^3, and if the inverse-Compton emission is dominated by scattering of the cosmic microwave background radiation, $A_{\rm e} = 8.6 \times 10^{-9}$ cm^{-3} GeV$^{\Gamma-1}$, $B = 10\ \mu$G, and $\epsilon_{\rm e} = 20$ TeV. Similar estimates of the magnetic field strength are reported by Tanimori et al. (1998, $B = 6.5 \pm 2\ \mu$G), Aharonian and Atoyan (1999, $B = 10\ \mu$G), and Dyer et al. (2000, $B = 10\ \mu$G). However, Allen et al. (2001) argue that the magnetic field is substantially larger than 10 μG and arbitrarily use a value of 40 μG. This value for the magnetic field lies comfortably between the compressed value ($B \approx 10\ \mu$G) and the value obtained using the minimum-energy condition ($B \approx 100\ \mu$G). For the remainder of the discussion, it is assumed that $B = 40\ \mu$G and that the cosmic-ray electron spectrum is specified by equation 1 with parameters appropriate for this field strength (i.e. $A_{\rm e} = 2.4 \times 10^{-9}$ cm^{-3} cm$^{\Gamma-1}$, $\Gamma_{\rm e} = 2.14$, and $\epsilon_{\rm e} = 10$ TeV). The inferred spectrum of cosmic-ray electrons is shown in figure 5 using these parameters.

Although there is no evidence that cosmic-ray nuclei are

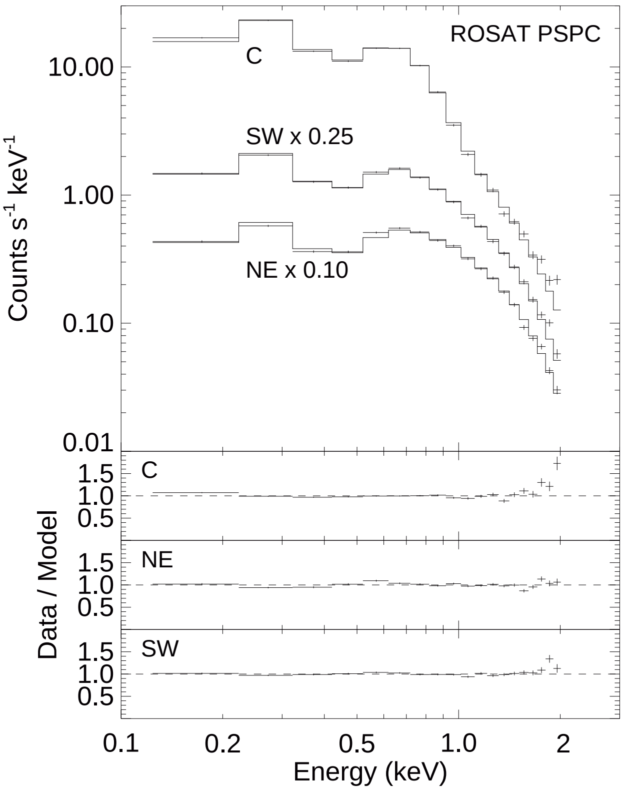

Fig. 3. The *ROSAT* PSPC data of spatially-separate north-eastern (NE), south-western (SW), and central (C) regions of SN 1006. Refer to the caption of fig. 1.

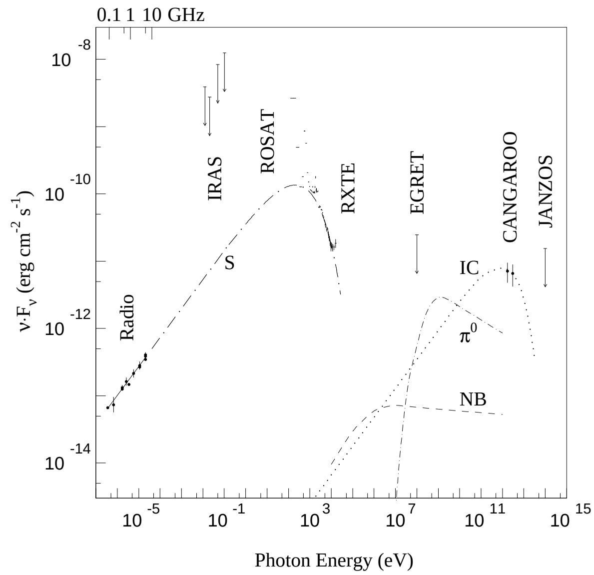

Fig. 4. The radio to gamma-ray photon energy-flux spectrum of SN 1006. The data, which are labeled vertically, include the radio results of Kundu (1970), Milne (1971), Milne and Dickel (1975), Stephenson et al. (1977), and Roger et al. (1988), the IRAS infrared upper limits of Arendt (1989), the *ROSAT* PSPC and *RXTE* PCA results of this paper, the EGRET gamma-ray upper limit of Hartman et al. (1999, fig. 3), the gamma-ray results of the CANGAROO collaboration (Tanimori et al. 1998), and the gamma-ray upper limit of the JANZOS collaboration (Allen et al. 1995). The four model spectra are estimates of the photon energy fluxes produced by synchrotron radiation (S), inverse Compton scattering on the cosmic microwave background radiation (IC), the decay of neutral pions (π^0), and bremsstrahlung emission of the non-thermal electrons (NB). The non-thermal bremsstrahlung and π^0 spectra were computed assuming the density of protons in the remnant is 1.2 cm^{-3} (i.e. $n_{\rm p} = 4n_0$).

accelerated in SN 1006 (cf. Aharonian and Atoyan (1999)), Ellison and Reynolds (1991) suggest that relativistic electrons and nuclei are accelerated in a similar manner. Therefore, we estimate the parameters of the cosmic-ray nuclei spectra. For simplicity, only hydrogen and helium nuclei are considered. The non-thermal spectra of these particles are assumed to have the same functional form as equation 1. The spectral indices of the protons and alpha particles are assumed to be the same as the spectral index of the electrons ($\Gamma_{\rm p} = \Gamma_{\rm He} = \Gamma_{\rm e} = 2.14$). The exponential cut-off energies of the different cosmic-ray particles are assumed to be related by the magnetic rigidity of the particles (i.e. $\epsilon_{\rm p} = \frac{1}{2}\epsilon_{\rm He} = \epsilon_{\rm e} = 10$ TeV). This relationship is appropriate if the maximum energy of the electrons is limited by the escape of the particles from the remnant (Reynolds (1996); Dyer et al. (2001)), but it is not appropriate if $\epsilon_{\rm e}$ is limited by radiative losses. The values of $A_{\rm p}$ and $A_{\rm He}$ are determined assuming that the ratio of the total number density of protons, helium nuclei, and electron is $n_{\rm p} : n_{\rm He} : n_{\rm e} = 1 : 0.02 : 1.04$ and that the fractional numbers of non-thermal protons and helium nuclei are the same as the fractional number of non-thermal electrons (i.e. $\eta \equiv n^{\rm cr}_{\rm p}/n_{\rm p} = n^{\rm cr}_{\rm He}/n_{\rm He} = n^{\rm cr}_{\rm e}/n_{\rm e}$). Using these relationships, $A_{\rm p} = 1.1 \times 10^{-6}$ cm^{-3} GeV$^{\Gamma-1}$, $A_{\rm He} = 1.0 \times 10^{-7}$ cm^{-3} GeV$^{\Gamma-1}$, and $\eta = 5 \times 10^{-4}$ (Allen et al. (2001)). Our assumptions about the shapes of the cosmic-ray spectra and about the relative numbers of non-thermal protons and electrons yield a number density of protons that is 160 times larger than the number density of electrons at 1 GeV (i.e. $dn^{\rm cr}_{\rm p}/dE = 160\, dn^{\rm cr}_{\rm e}/dE$ at 1 GeV, fig. 5). Within the rather large uncertainties of our estimates, this ratio is consistent with the ratio observed at Earth (Meyer (1969)).

The estimates of the parameters of the cosmic-ray spectra of SN 1006 have important implications for Galactic cosmic-ray acceleration. It is generally accepted that Galactic cosmic rays are accelerated predominantly in the shocks of supernova remnants. If this hypothesis is true, an average supernova remnant should transfer a sufficient amount of energy to cosmic rays, produce a cosmic-ray proton spectrum that has an appropriate spectral index, and accelerate protons to energies high enough to explain the properties of the cosmic rays observed at Earth. The energies in cosmic-ray electrons, protons, and helium nuclei can be obtained by performing the integral $\int dE E(dn/dE)$. This computation yields cosmic-ray electron, proton, and helium energies of 9×10^{47}, 1×10^{50}, and 8×10^{48} erg, respectively (Allen et al. (2001)). The sum

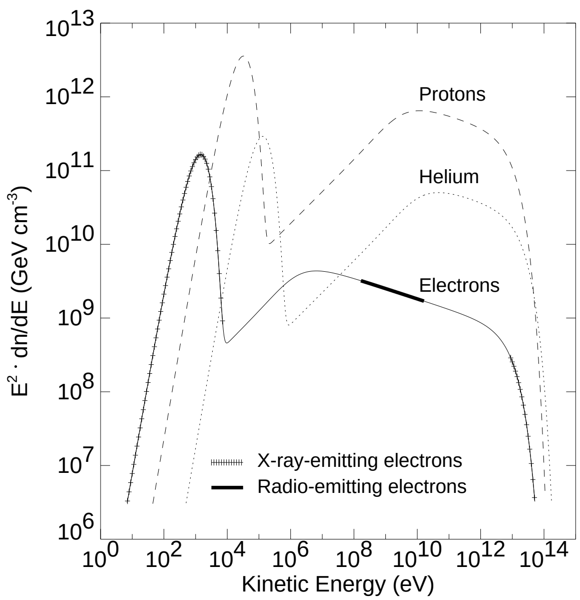

Fig. 5. Estimates of the cosmic-ray electron, proton, and helium spectra of SN 1006. The low-energy and high-energy ends of the electron spectrum produce the observed thermal and non-thermal X-ray emission, respectively. The GeV electrons produce the observed radio emission. The ratio of the number densities of protons and electrons at 1 GeV is about 160, which is consistent with the ratio observed at Earth. The total cosmic-ray energy is dominated by the energy of the cosmic-ray protons.

of these three energies, $E_{\rm cr} = 1 \times 10^{50}$ erg, is dominated by the energy in cosmic-ray protons. This energy is consistent with the average amount of energy a supernova remnant would have to transfer to cosmic rays over the lifetime of the remnant (0.3–3 $\times\, 10^{50}$ erg, Drury et al. (1989)). The differential spectral index of the electron spectrum of SN 1006 at GeV energies ($\Gamma_{\rm e} = 2.14 \pm 0.12$) is consistent with the expected spectral index of the relativistic cosmic-ray proton spectra produced by the accelerators of Galactic cosmic rays ($\Gamma_{\rm p} = 2.80 \pm 0.04 - 0.6 = 2.2$, Asakimori et al. (1998); Swordy et al. (1990)).

SN 1006 may or may not accelerate particles to energies as high as the energy of the "knee" feature at about 3000 TeV in the all-particle cosmic-ray spectrum observed at Earth. If the mechanism responsible for the acceleration of Galactic cosmic rays depends on the magnetic rigidity of the particles, which is true for diffusive shock acceleration in supernova remnants, it may be the case that the cosmic-ray particles at 3000 TeV are principally iron and that protons are accelerated to energies of only about 100 TeV (Lagage and Cesarsky (1983)). The estimated cut-off energy of the electron spectrum of SN 1006 ($\epsilon_{\rm e} = 10$ TeV), while uncertain, is lower than 100 TeV. Since relativistic electrons and protons that have the same energy have the same magnetic rigidity, the maximum energy of the protons is expected to be the same as the maximum energy of the electrons unless the maximum energy of the electrons is regulated by radiative losses. If the magnetic field $B = 40\ \mu$G, an electron with an energy $E = \epsilon_{\rm e} = 10$ TeV radiates half of its energy in about 400 yr. Since this time is less than the age of the remnant, the maximum energy of shock-accelerated electrons may be limited by synchrotron losses. In this case, the value of the energy $\epsilon_{\rm e}$ represents a lower limit on the exponential cut-off energy of the proton spectrum because radiative losses are only important for electrons, not nuclei. Therefore, the maximum energy of the protons in SN 1006 may be consistent with the expected value of $\epsilon_{\rm p} = 100$ TeV. However, if the magnetic field strength is significantly smaller that $40\ \mu$G, the maximum energy of the electrons may be regulated by the free escape of the particles from the remnant (Reynolds (1996); Dyer et al. (2001)). In this case, the maximum energy of the protons is the same as the maximum energy of the electrons and is well below 100 TeV. SN 1006 is clearly a significant source of Galactic cosmic rays (at least cosmic-ray electrons), but the remnant may or may not be capable of accelerating particles to energies as high as the energy of the knee.

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