Evidence of 10–100 TeV Electrons in Supernova Remnants

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Abstract

Analyses of the X-ray data of the five young shell-type supernova remnants Cas A, Kepler, Tycho, SN 1006, and RCW 86 suggest that some of the X-ray emission of these sources is non-thermal. This non-thermal emission is qualitatively consistent with models of the broad-band (radio-to-X-ray) synchrotron spectra of remnants and does not seem to be consistent with other non-thermal X-ray emission processes. If this emission is produced by synchrotron radiation, the radio-to-X-ray synchrotron spectra imply that the electron spectra have differential spectral indices of about 2.2 and exponential cut offs at energies ~ 10 TeV. If the remnants also accelerate cosmic-ray nuclei, the total energies of the cosmic rays in the remnants are estimated to be ~ 1–5×10^{49} erg. Therefore, the shapes of the cosmic-ray electron spectra, the maximum energies of the cosmic-ray electrons, and the total cosmic-ray energies of the five young remnants seem to be consistent with the idea that Galactic cosmic rays are predominantly accelerated in the shocks of supernova remnants.

1 Introduction:

For many years the X-ray emission of shell-type (as opposed to plerionic) supernova remnants was modeled in terms of only the emission of hot thermal plasmas. However, it has recently become clear that at least some young shell-type supernova remnants (SN 1006, Koyama et al. 1995, Allen et al. 1999; Cas A, Allen et al. 1997; G347.3$-$0.5, Koyama et al. 1997; IC 443, Keohane et al. 1997) produce non-thermal emission as well. At least for SN 1006 and Cas A, the only plausible description of the non-thermal X-ray emission is synchrotron emission by 10–100 TeV electrons (Allen et al. 1999; Allen et al. 1997). The non-thermal X-ray spectra of these two remnants are qualitatively consistent with simple models of the radio-to-X-ray synchrotron spectra, but are inconsistent with the predicted shapes and flux levels of other processes such as bremsstrahlung emission or inverse Compton scattering of the cosmic microwave background radiation (fig. 1). Furthermore, the high-energy (i.e. non-thermal–dominated) X-ray images differ substantially from lower-energy (thermal-dominated) X-ray images (Willingale et al. 1996; Holt et al. 1994; Vink et al. 1999), but are similar to the radio synchrotron images of the remnants (Reynolds and Gilmore 1986; Anderson and Rudnick 1995). These two clues provide very-strong support for the idea that the non-thermal X-ray emission of SN 1006 and Cas A is synchrotron radiation. The presence of very-high–energy electrons in SN 1006 is corroborated by the detection of TeV gamma-ray emission from this remnant (Tanimori et al. 1998)

These results have very important implications for the study of Galactic cosmic-ray acceleration. Galactic cosmic rays, up to an energy of about 3000 TeV (the "knee"), are thought to be predominantly accelerated in the shocks of supernova remnants. Since the shock-acceleration process of supernova remnants depends on the magnetic rigidity of the particles, it may be the case that the cosmic-ray particles at 3000 TeV are principally iron and that protons (and electrons) are only accelerated to energies of about 100 TeV (Lagage and Cesarsky 1983). However, it has been difficult to confirm that supernova remnants accelerate particles to such high energies. Although previous radio and gamma-ray observations of remnants reveal evidence of non-thermal particles in many supernova remnants, these results are limited to particle energies ($\lesssim 10$ GeV) that are well below 100 TeV (except for the TeV gamma-ray results of Tanimori et al. 1998). The non-thermal X-ray data of SN 1006 provided the first evidence that supernova remnants accelerate particles to very-high energies (Koyama et al. 1995; Reynolds 1996). Subsequent observations reveal that such X-ray emission is not unique to SN 1006 (Allen et al. 1997; Koyama et al. 1997; Keohane et al. 1997). Simple models of the radio-to-X-ray synchrotron spectra of supernova remnants (Reynolds 1998) have been used to show that the electron spectra of SN 1006 and Cas A have exponential cut offs with e-folding energies $\epsilon \sim 20$ and 5 TeV, respectively. Therefore, the study of the non-thermal X-ray emission of young shell-type supernova remnants provides a powerful means of studying the acceleration of the highest-energy cosmic-ray electrons in situ.

2 Data and Analyses:

Several supernova remnants have been observed using the Proportional Counter Array (PCA) on the Rossi X-Ray Timing Explorer satellite. The PCA is a spectrophotometer comprised of an array of five co-aligned proportional counter units that are mechanically collimated to have a field-of-view of 1° FWHM (Jahoda et al. 1996). We have analyzed PCA data for the five, young, shell-type remnants Cas A, Kepler, Tycho, SN 1006, and RCW 86. These data were screened to exclude the time intervals during which (1) one or more of the five proportional counter units was off, (2) the elevation of the source above the limb of the Earth $< 10^\circ$, (3) the PCA background model is not well behaved, and (4) the nominal pointing direction of the PCA $> 0\overset{\circ}{.}02$ from the specified direction of the source. After applying these selection criteria, 169, 44, 81, 18, and 32 ks of data were used to construct the X-ray spectra of Cas A, Kepler, Tycho, SN 1006, and RCW 86, respectively.

The results of the spectral analyses are shown in figure 2. The spectral data below 10 keV for Cas A, Kepler, Tycho, and RCW 86 and below 7 keV for SN 1006 are excluded to insure that the spectra of the remnants are dominated by non-thermal emission.

3 Discussion and Conclusion:

At energies above 10 keV, non-thermal X-ray emission dominates the spectra of both SN 1006 and Cas A. Both of these spectra can be described by power laws with photon indices of $\Gamma = 3.0 \pm 0.2$ (Allen et al. 1997; Allen et al. 1999). As shown in figure 2, similar results are obtained for the remnants Kepler ($\Gamma = 3.0 \pm 0.2$), Tycho ($\Gamma = 3.2 \pm 0.1$), and RCW 86 ($\Gamma = 3.3 \pm 0.2$). Therefore, the high-energy non-thermal X-ray spectra of the five remnants may be produced by a common emission mechanism. Since the high-energy non-thermal X-ray spectra of SN 1006 and Cas A are produced by synchrotron radiation from 10–100 TeV electrons, the results shown in figure 2 support the conclusion that all young shell-type supernova remnants accelerate electrons to very–high-energies. If more detailed analyses of the X-ray emission of Kepler, Tycho, RCW 86, and other young shell-type supernova remnants confirm this conclusion, the results will have very important implications for the origins of Galactic cosmic rays.

The energy at which the radio-to-X-ray synchrotron spectra roll over (see fig. 1) can be used to determine the exponential cut-off energy of the electron spectra of the remnants. For example, if the magnetic field strength of SN 1006 ~ 10 μG (Tanimori et al. 1998) and the energy of the roll off in the synchrotron spectrum ~ 100 eV (fig. 1), the e-folding energy of the cut off in the electron spectrum of SN 1006 $\epsilon \sim 20$ TeV. Estimates of the e-folding energies of the cut offs in the electron spectra of the other remnants yield similar results ($\epsilon \sim 5$, 20, 10, and 10 TeV for Cas A, Kepler, Tycho, and RCW 86, respectively). Since these results are sensitive to the assumed shape of the electron spectrum and the strength of the magnetic field, they should be regarded as order-of-magnitude estimates. Nevertheless, it is interesting that all five of the estimates are below 100 TeV. If the estimates are accurate, the results may indicate that the cosmic-ray electrons in the five remnants have not yet reached their maximum energy, that these remnants do not accelerate cosmic-ray electrons to energies above ~ 10 TeV, or that the maximum energy of the electrons (but not the nuclei) is regulated by radiative losses. More work is needed to differentiate between these possibilities.

Two other clues support the idea that Galactic cosmic rays are accelerated in the shocks of supernova remnants. One clue is the typical electron spectral index of the young remnants of figure 2. A review of radio spectral indices of the five remnants ($\alpha = 0.77$, 0.64, 0.61, 0.57, and 0.6 for Cas A, Kepler, Tycho, SN 1006, and RCW 86, respectively, Green 1998) reveals that the typical differential spectral index of the electrons producing the radio spectra is about $\Gamma = 2.2$ ($= 2\alpha+1$). This index is consistent with the index expected for cosmic-ray accelerators because the observed differential spectral index of the cosmic-ray protons observed at Earth ($\Gamma = 2.8$, Asakimori et al. 1998) less the inferred spectral steepening due to an energy-dependent escape of the cosmic rays from the Galaxy ($\Delta\Gamma = 0.6$, Swordy et al. 1990) is about 2.2.

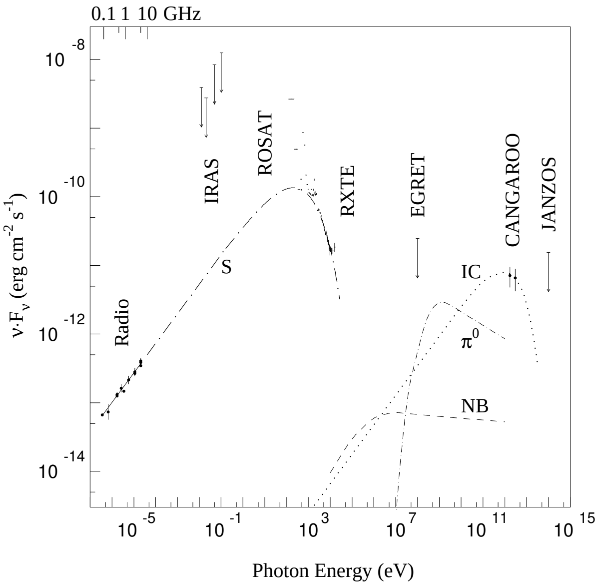

Figure 1: The multi-wavelength photon spectrum of SN 1006. The four broken curves are estimates of the fluxes from synchrotron radiation (S), non-thermal bremsstrahlung emission (NB), inverse Compton scattering of the cosmic microwave background radiation (IC), and the decay of neutral pions (π^0). The details about the spectral data and the estimates of the photon spectra are described in detail by Allen et al. (1999). In contrast to the other emission processes, the synchrotron spectral model is consistent with both the shape and the flux level of the high-energy X-ray spectrum of SN 1006.

The second clue also stems from an analysis of the radio spectral data. The radio data of a remnant may be used to estimate the total energy of the cosmic-ray particles in the remnant. Such estimates depend on some assumptions about the strengths of the magnetic fields and about the cosmic-ray electron and proton spectra of the remnants. For simplicity, we assume (1) that the magnetic fields of the remnants are $B = 10^3$, 10^2, 10^2, 10, and 10^2, for Cas A, Kepler, Tycho, SN 1006, and RCW 86, respectively, (2) that the cosmic-ray electron and proton spectra are described by $dN_{\mathrm{e,p}}/dE \propto (E + m_{\mathrm{e,p}}c^2)(E^2 + 2m_{\mathrm{e,p}}c^2E)^{-(\Gamma+1)/2}e^{-E/\epsilon}$ (Bell 1978), (3) that the high-energy spectral indices (Γ ($= 2\alpha+1$) of the electrons and protons are the same, (4) that the e-folding energy of the exponential cut offs $\epsilon = 10$ TeV, and (5) that non-thermal electrons outnumber non-thermal protons by a factor of 1.2. The last assumption follows from the assumptions that the relative elemental abundances of the cosmic rays are comparable to the relative elemental abundances of the solar system and that all hydrogen and helium nuclei are fully ionized. This set of assumptions naturally leads to the result that cosmic-ray protons outnumber cosmic-ray electrons by a factor ~ 100 at 1 GeV, as is observed at Earth. Using these assumptions, we find that, at the present, the total energies of the cosmic-ray particles in the remnants $U_{\mathrm{cr}} \sim 5$, 2, 1, 2, and 1×10^{49} erg for Cas A, Kepler, Tycho, SN 1006, and RCW 86, respectively. These order-of-magnitude estimates are comparable to estimates of the total energy that is needed, on average, per remnant, over their lifetimes (~ 3–10×10^{49} erg, Blandford and Eichler 1987; Lingenfelter 1992).

In summary, analyses of the high-energy X-ray spectra of five young supernova remnants suggest that the remnants have similar non-thermal spectral properties at energies $\gtrsim 10$ keV. These spectra are qualitatively consistent with models of the radio-to-X-ray synchrotron spectra of supernova remnants. If this emission is produced by synchrotron radiation, the radio-to-X-ray synchrotron spectra imply that the electron spectra have differential spectral indices of about 2.2 and exponential cut offs at energies ~ 10 TeV. If the remnants also accelerate cosmic-ray nuclei, the total energies of the cosmic rays in the remnants are estimated to be ~ 1–5×10^{49} erg. These results appear to be consistent with the idea that Galactic cosmic-ray electrons (and, presumably, nuclei) are predominantly accelerated in the shocks of supernova remnants.

References

Allen, G. E. et al. 1997, ApJ, 487, L97
Allen, G. E. et al. 1999, In preparation
Anderson, M. C., & Rudnick, L. 1995, ApJ, 441, 307
Asakimori, K. et al. 1998, ApJ, 502, 278
Bell, A. R. 1978, MNRAS, 182, 443
Blandford, R. & Eichler, D. 1987, Phys. Rep., 154, 1
Holt, S. S., et al. 1994, PASJ, 46, L151
Jahoda, K., et al. 1996, in EUV, X-ray and Gamma-ray Instrumentation for Space Astronomy VII, ed. Siegmund, O. H. W, & Grummin, M. A. Proc. SPIE, 2808, 59
Keohane, J. W. et al. 1997, ApJ 484, 350
Koyama, K. et al. 1995, Nature, 378, 255
Koyama, K. et al. 1997, PASJ, 49, L7
Lagage, P. O., & Cesarsky, C. J. 1983, A&A, 125, 249
Lingenfelter, R. E. 1992, In The Astronomy and Astrophysics Encyclopedia, Edited by Maran, S. 139, Van Nostrand Reinhold Publishers
Reynolds, S. P. 1996, ApJ, 459, L13
Reynolds, S. P. 1998, ApJ, 493, 375
Reynolds, S. P., & Gilmore, D. M. 1986, AJ, 92, 1138
Swordy, S. P. et al. 1990, ApJ, 349, 625
Tanimori, T. et al. 1998, ApJ, 497, L25
The, L.-S., et al. 1996, A&ApS, 120, 357
Vink, J. et al. 1999, A&A, In press
Willingale, R., et al. 1996, MNRAS, 278, 749

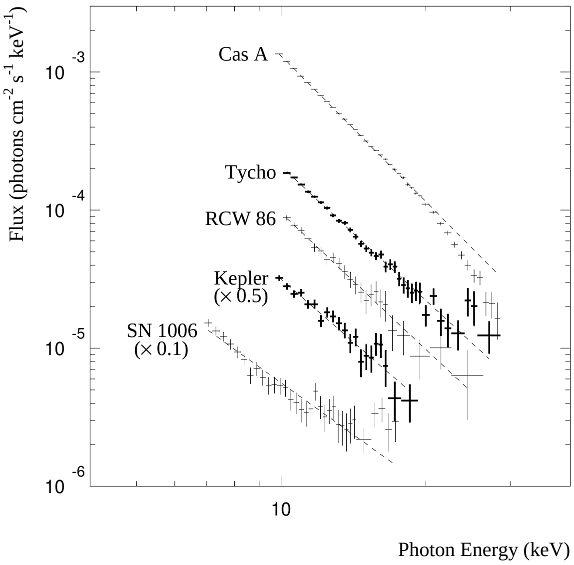

Figure 2: The PCA high-energy X-ray spectra of the young shell-type supernova remnants Cas A, Tycho, RCW 86, Kepler, and SN 1006. The spectra of Kepler and SN 1006 have been multiplied by factors of 0.5 and 0.1, respectively, to help distinguish one spectrum from the others. The high-energy X-ray spectra of the remnants are non-thermal and have very similar spectral shapes. Since the high-energy non-thermal emission of Cas A and SN 1006 are produced by X-ray synchrotron emission (Allen et al. 1997; Allen et al. 1999), it appears that the high-energy X-ray spectra of Kepler, Tycho, and RCW 86 may also be produced by X-ray synchrotron emission.