29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

Spatially-Resolved Spectroscopy of X-Ray Synchrotron-Emitting Regions in Some Historical Shell-Type Supernova Remnants

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We present *Chandra* data for the supernova remnant Cas A. X-ray spectra for roughly arcsecond-sized regions were fitted with a simple model that includes a bremsstrahlung continuum and fifteen Gaussian emission lines. The results of this analysis reveal that the faint, narrow, continuum-dominated filaments around the outer edges of the remnant have unusually high fitted electron temperatures. Since the emission from these regions is thought to be dominated by synchrotron radiation instead of thermal bremsstrahlung, the spectrum at each one of about ten thousand locations along these filaments was subsequently fitted with a synchrotron model. The critical frequency associated with the exponential cut-off energy of the electron spectrum is determined by the fits and is found to vary from one location to another. The fitted frequencies and a previously published estimate of the forward-shock velocity are used to show that the electron diffusion coefficient is comparable to the Bohm coefficient for the regions where the critical frequency is largest. In these regions, electrons are accelerated about as fast as possible and the maximum electron energy is limited by synchrotron losses. Similar results were also obtained for the remnants Kepler and Tycho.

1. Introduction

The sites at which Galactic cosmic rays are accelerated has been an active area of research for many decades. The shocks of supernova remnants have been a favorite for some time. Radio observations show that many remnants contain synchrotron-producing electrons at energies ~ 1 GeV. Since some of these synchrotron spectra are observed to extend to X-ray energies, some remnants are capable of accelerating electrons to energies as high as $\sim$ 10–100 TeV. Gamma-ray observations confirm that at least a few remnants produce very-high–energy particles. Although electrons represent only a small fraction of the cosmic-ray energy, analyses of X-ray synchrotron data can provide a considerable amount of information about the particle-acceleration process in supernova remnants. This claim is particularly true now that it is possible to use *Chandra* data to study the spectral properties of remnants on arcsecond spatial scales because the regions dominated by nonthermal emission are thin filaments whose spectral properties vary from one location to another along a filament.

2. Data and Analysis

Data from the twelve *Chandra* ACIS observations of Cas A whose exposure times were greater than 40 ks were used for the present analysis. One 70 ks observation was excluded because the transmission gratings were inserted, which greatly reduced the number of events in zeroth order. Collectively, a total of 1.09 Ms of Cas A data (350 million events) was analyzed. The data were reprocessed and filtered using the standard techniques described on the *Chandra* web site. (Analyses of *Chandra* ACIS data for Kepler and Tycho were performed in a similar manner.)

Spatially-resolved spectroscopic analyses were performed using ISIS and S-Lang [1]. A square grid, where each vertex is separated from an adjacent vertex by $1''$ in right ascension or $1''$ in declination, was placed over Cas A. Source spectra were extracted at each grid point across the entire extent of the remnant. If necessary,

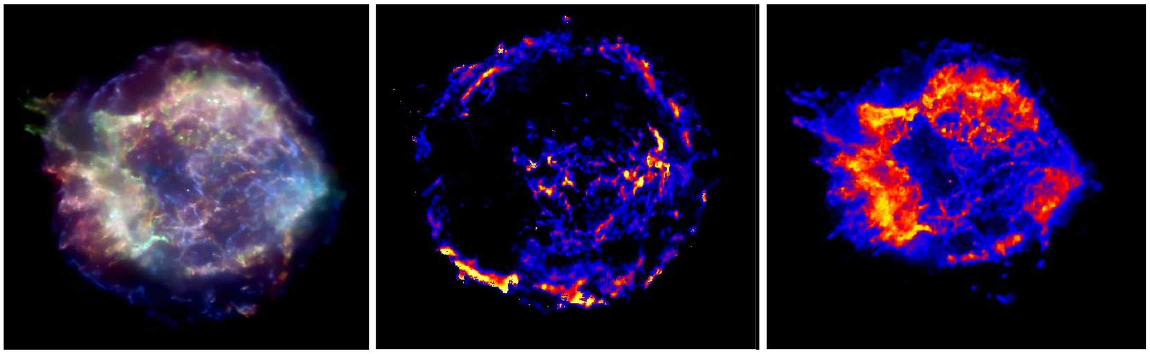

Figure 1. *Left*: A *Chandra* ACIS counts image (log scaling) of Cas A where the red, green and blue colors correspond to the energy bands 0.5–1.5 (i.e. the oxygen, iron, neon and magnesium emission lines), 1.5–2.5 (i.e. the silicon and sulfur emission lines) and 4.0–6.0 keV (i.e. the high-energy continuum), respectively. *Middle*: An image of the fitted bremsstrahlung electron temperature (linear scaling). The values range from about 0.8 keV (blue) to 6.2 keV (yellow). *Right*: An image of the fitted silicon Kα emission line flux (log scaling). The faint, continuum-dominated (i.e. blue-colored) filaments around the outer perimeter of Cas A have relatively hard spectra (i.e. high apparent electron temperatures) and little evidence of line emission.

the size of the extraction region for each spectrum was expanded from $1'' \times 1''$ in increments of $1''$ until the region included at least 10,000 counts. The region sizes used varied from $1'' \times 1''$ for the brightest parts of Cas A to $8'' \times 8''$ for the faintest parts. Initially, these spectra, some background spectra, position-dependent effective areas and position-dependent spectral-response matrices were used to fit the spectral data for each of the 105,000 regions with a bremsstrahlung continuum, fifteen Gaussian atomic emission lines and an interstellar absorption component. The results of these fits were used to create images of the fitted parameters including the electron temperature and emission-line fluxes (e.g. Fig. 1).

A comparison of the three panels in Figure 1 reveals that the faint, blue, continuum-dominated filaments are strongly correlated with regions that have high fitted electron temperatures and low fitted emission-line fluxes. As explained in section 3, this emission is probably dominated by synchrotron radiation. Therefore, 10,300 regions with highest apparent electron temperatures were subsequently fitted with a synchrotron radiation model instead of a thermal bremsstrahlung model. The synchrotron spectrum is based on an electron spectrum that has a differential spectral index of 2.54 [2] at 1 GeV and an exponential cut-off at very-high energies. The results of the synchrotron analysis were used to create (among other things) an image (Fig. 2) of the critical frequency associated with the cut-off energy ϵ of the electron spectrum:

$$\nu_{\rm c} = 1.26 \times 10^{17} \left(\frac{\epsilon}{10\ {\rm TeV}}\right)^2 \left(\frac{B}{100\ \mu{\rm G}}\right)\ {\rm Hz}, \tag{1}$$

where B is the total magnetic field strength (not $B_\perp$).

3. Discussion

The faint blue filaments around the outer edge of Cas A have relatively high fitted electron temperatures and relatively low line fluxes. These features are the opposite of what is expected if the emission where thermal (e.g. compare the two spectra in the plot on the right-hand side of Fig. 2). With little evidence of thermal bremsstrahlung in these filaments, little nonthermal bremsstrahlung is expected because nonthermal

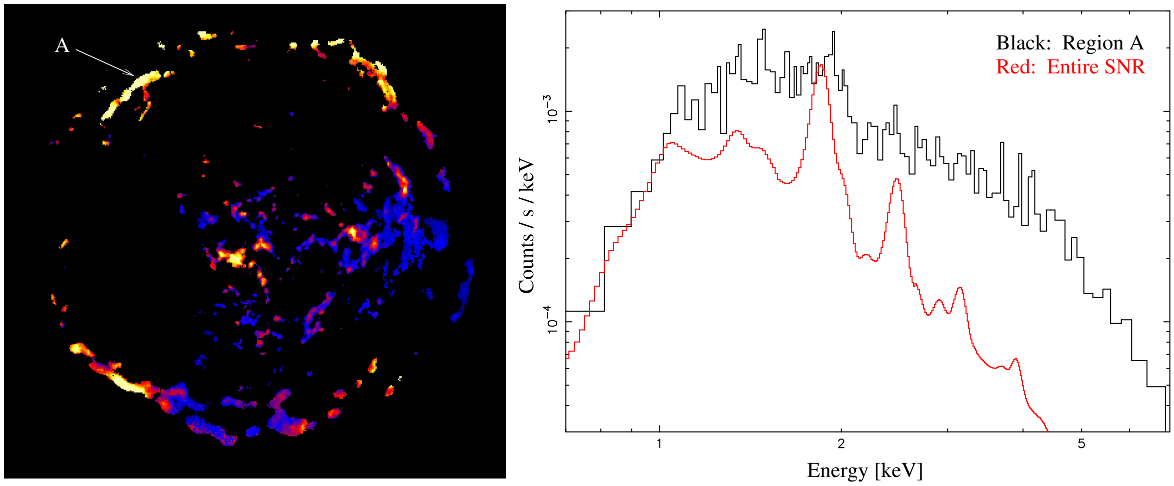

Figure 2. *Left*: An image of the fitted values of the critical frequency (square-root scaling). The values range from about 2.2×10^{16} Hz (blue) to 2.8×10^{18} Hz (white). *Right*: The background-subtracted spectra of the $1.5'' \times 1.5''$ box labeled region A (black) and of the entire Cas A remnant scaled by a factor of 4×10^{-6} (red). The spectrum of region A is relatively hard and, unlike the spectrum of the whole remnant, essentially featureless.

bremsstrahlung emission is produced by the nonthermal "tail" to the thermal electron distribution. Inverse Compton scattering of the cosmic microwave background radiation by GeV electrons also produces nonthermal X-ray emission, but this process is rather inefficient and the shape of the X-ray spectrum is incompatible with the expected shape of the inverse Compton spectrum. Therefore, the nonthermal emission around the outer edge of Cas A is most likely produced by synchrotron radiation from very-high–energy electrons accelerated at the forward shock.

When the regions with high fitted electron temperatures are fitted with a synchrotron model, the critical frequency is found to vary from one region to another (Fig. 2). The highest fitted frequency can be used to constrain the diffusion coefficient of the electrons at the cut-off energy of the electron spectrum. Since the mean rate of synchrotron losses cannot exceed the mean rate of energy gains at energies below the cut-off energy,

$$-\left(\frac{dE}{dt}\right)_{\rm sync} \leq \left(\frac{dE}{dt}\right)_{\rm acc} \tag{2}$$

in this range. Substituting the appropriate expressions into equation 2 yields, after a bit of algebra,

$$\frac{\bar{\kappa}}{\kappa_{\rm B}} \leq 18.7 \left(\frac{f}{0.15}\right) \left(\frac{u_1}{5000\ {\rm km\ s^{-1}}}\right)^2 \left(\frac{\nu_{\rm c}}{10^{17}\ {\rm Hz}}\right)^{-1}, \tag{3}$$

where $\bar{\kappa}$ is the mean electron diffusion coefficient at the cut-off energy, $\kappa_{\rm B}$ is the Bohm coefficient, $f = (r-1)/r(r+1)$, r is the compression ratio and u_1 is the speed of the upstream material relative to the shock. Equation 3 has the advantage that the upper limit on the diffusion coefficient is expressed almost exclusively in terms of observable properties of the remnant. If the critical frequency is as large as 2.8×10^{18} Hz in some regions of Cas A and if the forward-shock velocity is 5000 km s^{-1} [3], then electrons in these regions diffuse at the Bohm limit (i.e. are accelerated about as fast as possible, Table 1). The fact that the limit on $\bar{\kappa}/\kappa_{\rm B}$ is 0.7 (i.e. is less than one, Table 1) is not particularly troubling because just the statistical uncertainty of this ratio is about 20–30%.

Table 1. Limits on the Electron Diffusion Coefficient

Remnant	u_1 (10^3 km s^{-1})	Reference	ν_c (10^{17} Hz)	$\bar{\kappa}/\kappa_B$
Cas A	5.0	[3]	28	≤ 0.7
Kepler	2.0–2.5	[4]	1.5	≤ 2.2–3.4
Tycho	1.9–4.6	[5]	1.0	≤ 2.9–17

The inferred forward-shock velocity u_1, the maximum fitted synchrotron critical frequency ν_c and the inferred mean electron diffusion coefficient $\bar{\kappa}$ as a fraction of the Bohm diffusion coefficient κ_B.

Since the upper limit on the diffusion coefficient is computed by equating synchrotron losses and acceleration gains, a diffusion coefficient as small as the Bohm limit implies that the maximum electron energy is limited by synchrotron losses. Protons, which do not suffer from synchrotron losses, may be accelerated to energies higher than the maximum energy of the electrons.

4. Conclusions

We have performed spatially-resolved spectroscopic analyses of the young, shell-type supernova remnants Cas A, Kepler and Tycho. The results of these analyses show that the remnants exhibit evidence of synchrotron-dominated filaments around the outer edges of the sources. As expected, electrons seem to be accelerated to very-high energies at the forward shocks of the remnants. When the spectra of the synchrotron-dominated regions are fitted with a synchrotron model, the values of the critical frequencies of the synchrotron spectra are found to vary considerably from one region to another. In the regions with the highest critical frequencies, the fitted values of the frequency and previously-published results for the velocities of the forward-shock suggest that electrons are accelerated in the Bohm limit. Since the limits on the diffusion coefficient were computed by equating the rates of acceleration gains and synchrotron losses, the results also indicate that the maximum electron energy is limited by synchrotron losses in these regions.

5. Acknowledgements

We thank Don Ellison, who provided the initial spark for this work.

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