Nonthermal Bremsstrahlung vs. Synchrotron Radiation: Cas A

G. E. Allen¹, M. D. Stage², J. C. Houck¹.
¹Massachusetts Institute of Technology, Kavli Institute for Astrophysics and Space Research, 77 Massachusetts Avenue, NE80, Cambridge, MA 02139-4307
²University of Massachusetts, Department of Astronomy, LGRT-B 619E, 710 North Pleasant Street, Amherst, MA 01003-9305
gea@space.mit.edu

Abstract: We performed a spectral analysis of some Chandra ACIS and RXTE PCA data for the supernova remnant Cas A. A very large (1.1 Ms) ACIS data set is used to identify regions dominated by synchrotron radiation. The best-fit spectral models for these regions are combined to obtain a composite synchrotron model for the entire remnant. The difference between this model and the observed PCA flux is fitted with a nonthermal bremsstrahlung model. The results of this analysis suggest that (1) the ratio of the nonthermal bremsstrahlung to synchrotron radiation varies from about 2:1 to 4:1 in the 10–32 keV energy band, (2) the electron spectrum is significantly steeper at 10–32 keV than it is at 1 GeV, (3) about 5% of the electrons are nonthermal and (4) about 30% of the energy in the electron distribution is in nonthermal electrons.

Introduction

The nature of the high-energy X-ray emission from Cas A has been a source of controversy for at least the last decade. Some have suggested that the emission is dominated by synchrotron radiation from TeV electrons accelerated at the forward shock of the remnant [1]. Others argue that most of the emission is produced by nonthermal bremsstrahlung emission from electrons that have energies only slightly larger that the thermal electron energies [3, 7, 9]. The goal of the present analysis is to determine how much each mechanism contributes to the high-energy X-ray spectrum. The results will help determine the properties of the nonthermal electrons at energies just above the thermal peak.

Data and Analysis

The present work is based on an analysis of 1.1 Ms of Chandra ACIS data [6, 8] and 91 ks of RXTE PCA data [1]. As described by [8], the 0.3–7 keV ACIS data are used to identify the regions dominated by synchrotron radiation. These regions are

1. Note that the PCA is not an imaging instrument. It is not possible to separately measure the spectra of small regions of the source. Therefore, the spectra of the small regions studied using the ACIS data must be summed before they are compared to the PCA data.
Figure 1: A 1.1 Ms, color-coded, ACIS image of the supernova remnant Cas A. The red, green and blue features are associated with the 0.5–1.5 keV (O, Fe L, Ne and Mg emission-line), 1.5–2.5 (Si and S emission-line) and 4–6 keV (continuum) energy bands, respectively.

The noise ratio is less than one in this range. When the composite synchrotron spectrum derived from the ACIS data is compared to the PCA data, the results indicate that only a minority of the PCA flux is produced by synchrotron radiation. Therefore the PCA data were fitted with a model that includes two components: a synchrotron component and a nonthermal bremsstrahlung component. These components are described in detail by [5]. The synchrotron component is the composite synchrotron spectrum as extrapolated to PCA energy band. This component has no free parameters in the fit. Therefore, we assume that the relative calibration uncertainties of the ACIS and the PCA are negligible. The 10–32 keV emission in excess of the synchrotron radiation is fitted with a nonthermal bremsstrahlung component. While this model includes the low-energy correction of [4], the model is based on the assumption that the target particles are at rest. The nonthermal bremsstrahlung component has two free parameters: the differential spectral index of the nonthermal electron spectrum ($\Gamma$) and the normalization of the nonthermal bremsstrahlung emission. The best-fit parameters are listed in Table 1. The data (black histogram) and model (red histogram) for the PCA data are plotted in Figure 2. Most of the black histogram is obscured by the red histogram because these two histograms are nearly identical. The red histogram is the sum of the green (instrumental background), light blue (synchrotron model) and dark blue (nonthermal bremsstrahlung model) components. As shown, the energy-dependent ratio of the nonthermal bremsstrahlung and synchrotron components is about 2:1 to 4:1 in the 10–32 keV band. A combination of the results for the nonthermal bremsstrahlung model and the results for a separate, thermal bremsstrahlung analysis ($kT = 1$ keV, $N_{\text{norm}} = 2.32 \text{ cm}^{-5}$) are used to infer the properties of the global electron spectrum. This spectrum, which is shown in Figure 3, includes the following features:

Table 1. Best-fit parameters

| Parameter       | Value          |
|-----------------|----------------|
| $\Gamma$        | 4.14           |
| $\text{Norm} \ [\text{cm}^{-5} \text{ at} \ 1 \text{ GeV}]$ | 11.6           |

Figure 2: The PCA data (black) and background (green) spectra, the global synchrotron spectrum (light blue) and the nonthermal bremsstrahlung spectrum (dark blue) are plotted in the top panel. The red histogram is the sum of the background, synchrotron and nonthermal bremsstrahlung spectra. The bottom panel shows the differences between the nearly identical black and red histograms divided by the square root of the black histogram.
Figure 3: The thermal and nonthermal electron spectrum for the entire supernova remnant Cas A. The dashed red line marks the transition between the thermal and nonthermal bands. The dotted black curve shows what the thermal Maxwellian distribution would be if the remnant did not contain nonthermal electrons.

- There is a transition from the thermal Maxwellian to a nonthermal distribution at $E = 5.3$ keV ($p = 73$ keV/c).

- About 5% of the electrons have energies greater than 5.3 keV. This is one measure of the efficiency with which electrons are injected into the acceleration process in the remnant.

- The nonthermal electrons contain about 30% (i.e. $2 \times 10^{49}$ ergs) of the energy in the entire electron distribution.

**Conclusions**

By expanding on a previous analysis of the *Chandra* ACIS data for the supernova remnant Cas A [8], we have tried to separate the synchrotron emission of the remnant from the bremsstrahlung emission in the ACIS energy band (0.3–7 keV). An extrapolation of the total synchrotron model for the remnant from the ACIS energy band to the 10–32 keV energy band enabled us to model the excess PCA emission using a nonthermal bremsstrahlung component. The results of this analysis indicate that:

- About 70–80% of the 10–32 keV emission is produced by nonthermal bremsstrahlung (Fig. 2). The balance of the emission is produced by synchrotron radiation.

- The differential spectral index of the electrons that produce the nonthermal bremsstrahlung emission ($\Gamma = 4.1$) is significantly larger than the index of the radio-synchrotron–producing electrons ($\Gamma = 2.54$, [2]). This result may indicate that the spectral slope of the injected electrons is 4.1.

- A substantial fraction of the energy in the electron distribution is in nonthermal electrons (30%). If the same is true for nonthermal protons, then this result supports the idea that the shock has been modified by cosmic rays (i.e. cosmic rays are not test particles).

These conclusions should be regarded as preliminary because a number of potential concerns have not yet been investigated. These issues include:

- the possibility that the relative calibration of the *Chandra* ACIS and *RXTE* PCA is not negligible. Calibration differences could affect the fitted index and normalization of the nonthermal bremsstrahlung model and, hence, the properties of the inferred electron distribution.

- the possibility that the composite synchrotron spectrum is inaccurate because some of the X-ray synchrotron emission in the ACIS data has been overlooked. If this is true, then the amount of emission attributed to nonthermal bremsstrahlung may be too high.

- the assumption that the target particles in bremsstrahlung interactions are at rest. The cross section used for the nonthermal bremsstrahlung model may have to be modified.
Acknowledgements

GEA and JCH are supported by the contract SV3-73016 between MIT and the Smithsonian Astrophysical Observatory. The Chandra X-Ray Center at the Smithsonian Astrophysical Observatory is operated on behalf of NASA under the contract NAS8-03060. MDS has been supported by the NASA LTSA grant NAG5-9237 and the Five College Astronomy Department Fellowship program.

References

[1] G. E. Allen, J. W. Keohane, E. V. Gotthelf, R. Petre, K. Jahoda, R. E. Rothschild, R. E. Lingenfelter, W. A. Heindl, D. Marsden, D. E. Gruber, M. R. Pelling, and P. R. Blanco. Evidence of X-Ray Synchrotron Emission from Electrons Accelerated to 40 TeV in the Supernova Remnant Cassiopeia A. *ApJ*, 487:L97–L100, September 1997.

[2] J. W. M. Baars, R. Genzel, I. I. K. Pauliny-Toth, and A. Witzel. The absolute spectrum of CAS A - an accurate flux density scale and a set of secondary calibrators. *A&A*, 61:99–106, October 1977.

[3] J. A. M. Bleeker, R. Willingale, K. van der Heyden, K. Dennerl, J. S. Kaastra, B. Aschenbach, and J. Vink. Cassiopeia A: On the origin of the hard X-ray continuum and the implication of the observed O Viii Ly-alpha/Ly-beta distribution. *A&A*, 365:L225–L230, January 2001.

[4] G. Elwert. *Ann. Phys.*, 34:178–208, 1939.

[5] J. C. Houck and G. E. Allen. Models for Nonthermal Photon Spectra. *ApJS*, 167:26–39, November 2006.

[6] U. Hwang, J. M. Laming, C. Badenes, F. Berendse, J. Blondin, D. Cioffi, T. DeLaney, D. Dewey, R. Fesen, K. A. Flanagan, C. L. Fryer, P. Ghavamian, J. P. Hughes, J. A. Morse, P. P. Plucinsky, R. Petre, M. Pohl, L. Rudnick, R. Sankrit, P. O. Slane, R. K. Smith, J. Vink, and J. S. Warren. A Million Second Chandra View of Cassiopeia A. *ApJ*, 615:L117–L120, November 2004.

[7] J. M. Laming. Accelerated Electrons in Cassiopeia A: Thermal and Electromagnetic Effects. *ApJ*, 563:828–841, December 2001.

[8] M. D. Stage, G. E. Allen, J. C. Houck, and J. E. Davis. Cosmic-ray diffusion near the Bohm limit in the Cassiopeia A supernova remnant. *Nature Physics*, 2:614–619, September 2006.

[9] J. Vink and J. M. Laming. On the Magnetic Fields and Particle Acceleration in Cassiopeia A. *ApJ*, 584:758–769, February 2003.