The High-Energy X-Ray Spectrum of Cas A: Nonthermal Brem. v. Synchrotron Radiation

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Abstract

We performed a spectral analysis of some Chandra ACIS and RXTE PCA data for the supernova remnant Cas A. A 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 3:1 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.

1. 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. Allen et al. (1997) suggested that the emission is dominated by synchrotron radiation. Others have argued that most of the emission is produced by nonthermal bremsstrahlung (Bleeker et al. 2001; Laming 2001; Vink & Laming 2003). The goal of the present analysis is to determine how much each mechanism contributes to the high-energy X-ray spectrum.

2. Data

The present work is based on an analysis of 1.1 Ms of *Chandra* ACIS data (Hwang et al. 2004; Stage et al. 2006) and 91 ks of *RXTE* PCA data (Allen et al. 1997). As described by Stage et al. (2006), the ACIS data are used to identify the regions dominated by synchrotron radiation. These regions are the the ones with a relatively large fraction of their emission in the 4–6 keV band (i.e. the blue filaments in Fig. 1) or, equivalently, the ones with relatively large apparent electron temperatures (Fig. 2, Stage et al. 2006). The ACIS data is also used to characterize the properties of the synchrotron emission for each of these regions.

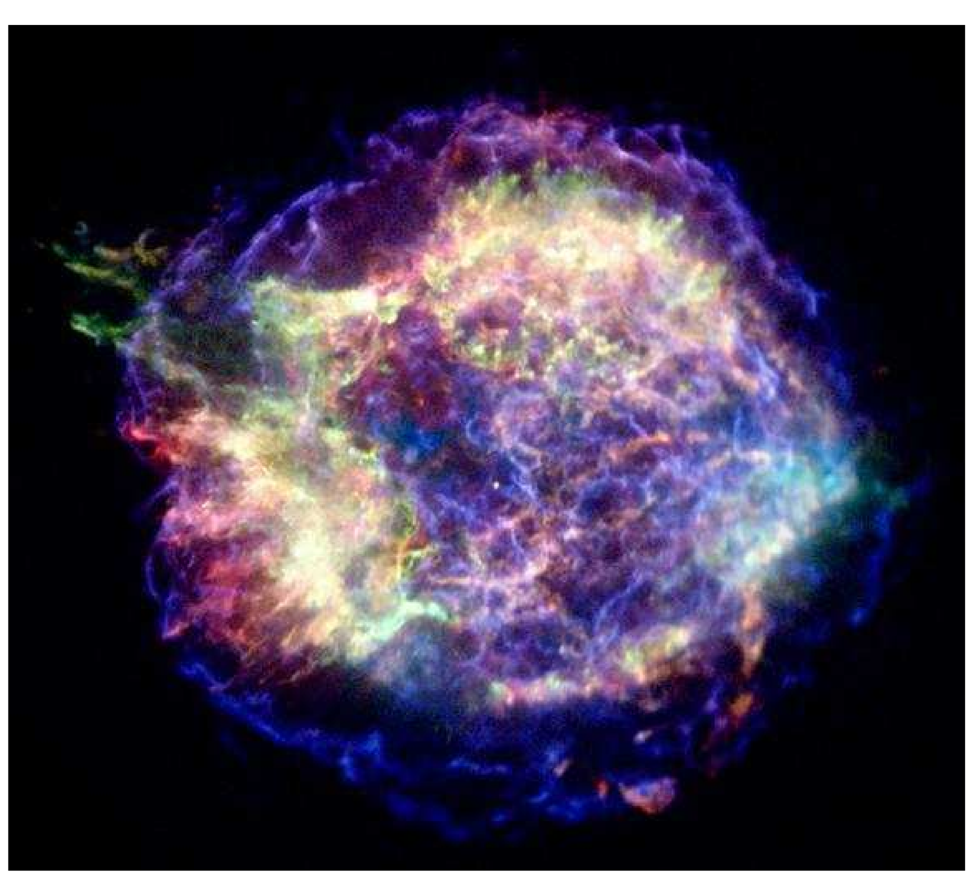

Figure 1: *A 1.1 Ms, color-coded, ACIS image of the supernova remnant Cas A. The red, green and blue features are associated with the 0.5–1.5 keV, 1.5–2.5 and 4–6 keV energy bands, respectively.*

The PCA data are used to characterize the nonthermal bremsstrahlung emission. By excluding the data below 10 keV, a thermal emission component and interstellar absorption can be neglected. The data above 32 keV are ignored because the signal-to-noise ratio is less than one in this range.

3. Model

The spectral model includes two components, a nonthermal bremsstrahlung component and a synchrotron component. The models of Houck & Allen (2006) are used for these components.

Since the synchrotron emission properties vary considerably from one region to another in Cas A, the composite synchrotron spectrum was obtained by summing the spectral models fitted to each of the synchrotron-dominated regions identified by Stage et al. (2006). The composite spectrum and two extreme examples of the synchrotron spectra of small regions are shown in Figure 2. Note that the composite spectrum has little curvature, even over two decades in energy. The composite spectrum was not allowed to vary during the fit. Furthermore, the relative calibration uncertainties of the ACIS and the PCA are assumed to be negligible.

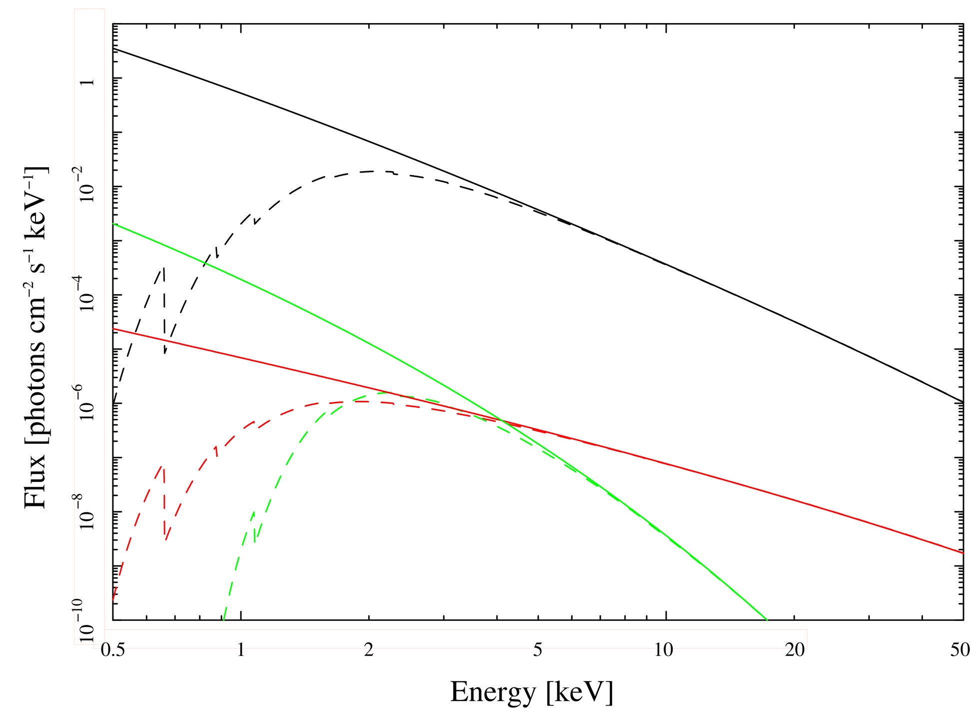

Figure 2: *The composite synchrotron spectrum (black) and two extreme synchrotron spectra (red and green) are shown. These spectra are plotted with and without interstellar absorption. Note that the column density toward the region with the red spectrum is substantially lower than the column density toward the region with the green spectrum.*

While the nonthermal bremsstrahlung model includes the low-energy correction of Elwert (1939), the model is based on the assumption that the target particles are at rest.

The two free parameters of the fit are the differential spectral index of the nonthermal electron spectrum (Γ) and the normalization of the nonthermal bremsstrahlung model.

4. Results

The best-fit parameters are listed in Table 1. The data, background, composite synchrotron spectrum and best-fit nonthermal bremsstrahlung model are shown in Figure 3.

A combination of the results for the nonthermal bremsstrahlung model and the results for a separate thermal bremsstrahlung analysis (kT = 1 keV, Norm = 2.32) are used to infer the properties of the global electron spectrum. This spectrum, which is shown in Figure 4, includes the following features:

- There is a transition from the thermal Maxwellian to a nonthermal distribution at 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% (2×10^{49} ergs) of the energy in the entire electron distribution.

Table 1. Best-fit nonthermal parameters

Parameter	Value
Γ	4.14
Norm [cm^{-5} at 1 GeV]	11.6

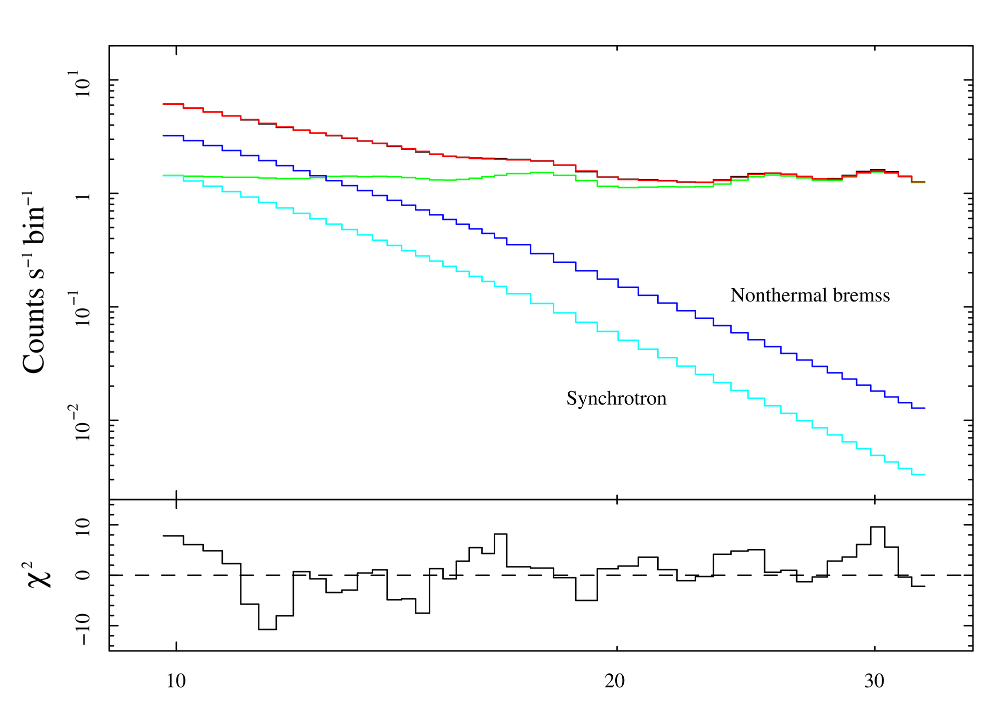

Figure 3: *The PCA data (black) and background (green) spectra, the composite synchrotron spectrum (light blue) and the nonthermal bremsstrahlung spectrum (dark blue) are plotted in the top panel. The red histogram is the sum of the background, composite synchrotron and nonthermal bremsstrahlung spectra. The bottom panel shows the differences between the black and red histograms divided by the square root of the number of counts.*

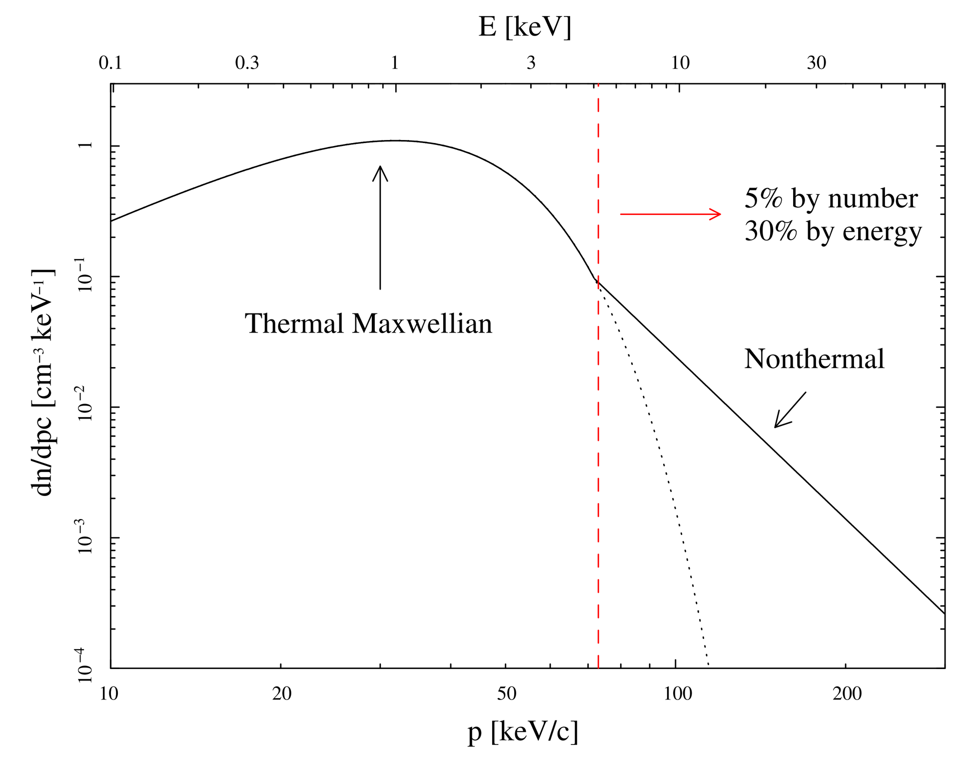

Figure 4: *The thermal and nonthermal electron spectrum for the entire supernova remnant Cas A. The dashed red line marks the transition between the thermal and nonthermal bands. The dotted curve shows what the thermal Maxwellian distribution would be if the remnant did not contain nonthermal electrons.*

5. Conclusions

- The best-fit results indicate that about two thirds to three quarters of the 10–32 keV emission is produced by nonthermal bremsstrahlung. The balance of the emission is produced by synchrotron radiation.
- The differential spectral index of the electrons that produce the nonthermal bremsstrahlung emission (Γ = 4.1) is significantly larger than the index of the radio-synchrotron–producing electrons (Γ = 2.54, Baars et al. 1977). This result may indicate that the spectral slope of the injected electrons is 4.1.
- A large 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).

6. Caveats

The results presented here are 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.

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