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Nonthermal Bremsstrahlung vs. Synchrotron Radiation: Cas A

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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 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 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.

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 suggest 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 [2, 3, 4]. 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 [5, 6] and 91 ks of *RXTE* PCA data [1]. As described by [6], the 0.3–7 keV ACIS data are used to identify the regions dominated by synchrotron radiation. These regions are 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 high apparent electron temperatures (Fig. 2 of [6]). Using a technique similar to the one described by [6], the 0.3–7 keV ACIS spectrum for each one of the nonoverlapping regions dominated by synchrotron radiation was fitted with a model that includes an interstellar absorption component and a synchrotron component. The composite 0.3–7 keV synchrotron spectrum of the entire remnant is obtained by summing the best-fit spectral models for each of the synchrotron-dominated regions. This composite model was extrapolated to higher X-ray energies and compared to the 10–32 keV PCA spectrum for Cas A[1]. The PCA data below 10 keV are excluded to simplify the analysis. A thermal emission component and an interstellar absorption component can be neglected at energies greater than 10 keV. The data above 32 keV are ignored because the signal-to-noise ratio is less than one in this range. When the composite syn-

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.

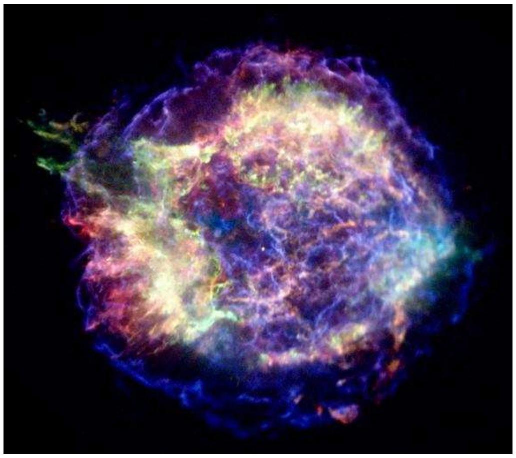

Figure 1: A 1.1 Ms, color-coded, ACIS image of the supernova remnant Cas A. The red, green and blue features are associated with the 0.5–1.5 keV (O, Fe L, Ne and Mg emission-line), 1.5–2.5 (Si and S emission-line) and 4–6 keV (continuum) energy bands, respectively.

chrotron 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 [7]. 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 are assuming that the relative calibration uncertainties of the ACIS and the PCA are negligible. The PCA emission in excess of the synchrotron radiation is fitted with a nonthermal bremsstrahlung component. While this model includes the low-energy correction of [8], 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 (Γ) 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

Table 1. Best-fit nonthermal parameters

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

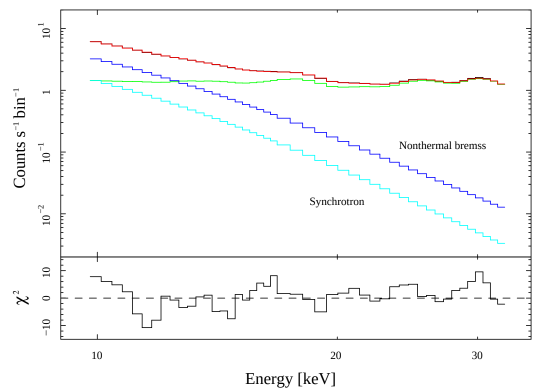

Figure 2: The PCA data (black) and background (green) spectra, the composite synchrotron spectrum (light blue) and the nonthermal bremsstrahlung spectrum (dark blue) are plotted in the top panel. The red histogram is the sum of the background, synchrotron and nonthermal bremsstrahlung spectra. The bottom panel shows the differences between the nearly identical black and red histograms divided by the square root of the black histogram.

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 3:1 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, $\mathrm{Norm} = 2.32$) are used to infer the properties of the global electron spectrum. This spectrum, which is shown in Figure 3, includes the following features:

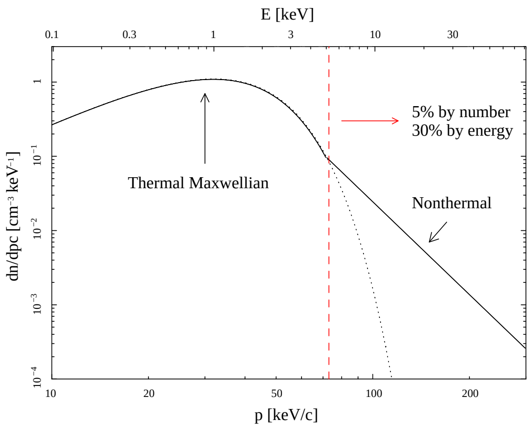

Figure 3: The thermal and nonthermal electron spectrum for the entire supernova remnant Cas A. The dashed red line marks the transition between the thermal and nothermal bands. The dotted black curve shows what the thermal Maxwellian distribution would be if the remnant did not contain nonthermal electrons.

- 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. 2×10^{49} ergs) of the energy in the entire electron distribution.

Conclusions

By expanding on a previous analysis of the *Chandra* ACIS data for supernova remnant Cas A [6], 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 two thirds to three quarters 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 (Γ = 4.1) is significantly larger than the index of the radio-synchrotron–producing electrons (Γ = 2.54, [9]). 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

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