Arcsecond-Scale Spectroscopy of Cas A and the Implications for Cosmic-Ray Acceleration

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Introduction

Studies of X-ray synchrotron radiation from Cas A and other young, shell-type supernova remnants have revealed that electrons are accelerated to very-high energies at the forward shock.

Here, we show that some of the electrons in Cas A are accelerated about as fast as possible (i.e. diffuse in the Bohm limit).

Data

Table 1. *Chandra* ACIS data used for Cas A

Date	Obsid	Exposure (ks)	No. of events (10^6)
2000-01-30	114	50	17
2002-02-06	1952	50	16
2004-02-08	5196†	51	16
2004-04-14	4638†	165	53
2004-04-18	5319†	42	14
2004-04-20	4636†	144	46
2004-04-22	4637†	165	53
2004-04-25	4639†	80	26
2004-04-28	4634†	150	48
2004-05-01	4635†	136	44
2004-05-05	5320†	56	18
Total		1088	350

†Hwang et al. 2004, ApJ, 615, L117

Challenges

- The observations include several pointings at different times with different roll angles and varying
  - detection efficiencies,
  - energy resolutions and
  - backgrounds.
    - –> The separate data sets should be analyzed jointly instead of combined.

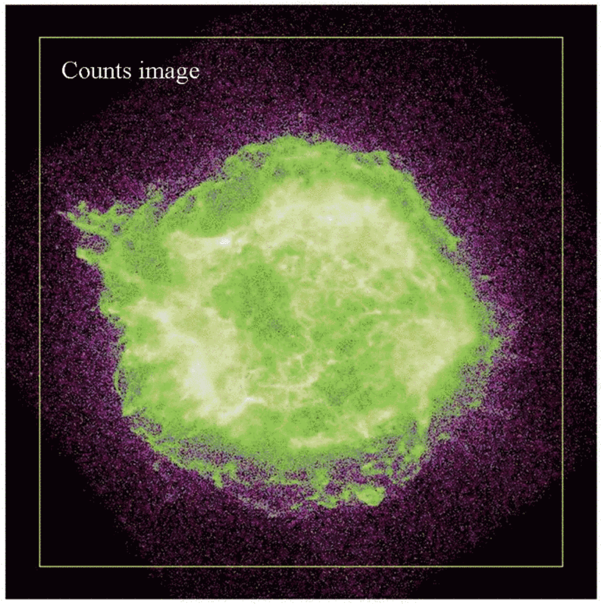
- The entire data set is large
  - 4750 events arcsec^{-2} over 73,500 arcsec^2
    - –> It is possible to perform arcsecond-scale spatially-resolved spectroscopy, but
    - –> This process is computationally intensive.

Analysis

The analyses were performed using a square grid that

- spans the entire remnant including the “jet” and “counterjet,”
- has adjacent points separated by $0.984''$ (i.e. 2 CCD pixels) and
- has 466 x 466 (217,156) points.

Outer Boundary of Grid

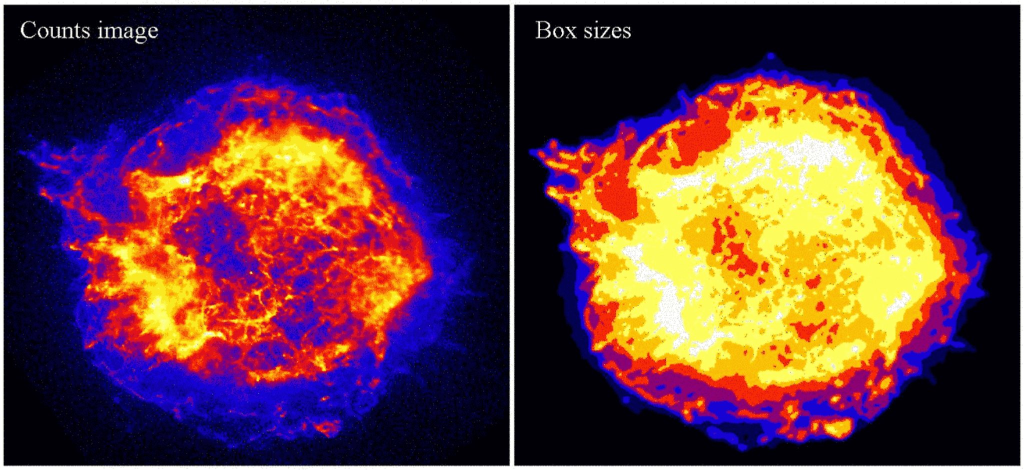


Spectral Extraction

A spectrum was extracted at each grid point.

- The square box was centered on the point.
- The width of the box was increased in 1″ increments (up to 15″) until the box contained at least 10,000 events.
  –> The boxes can overlap (i.e. are not independent)!

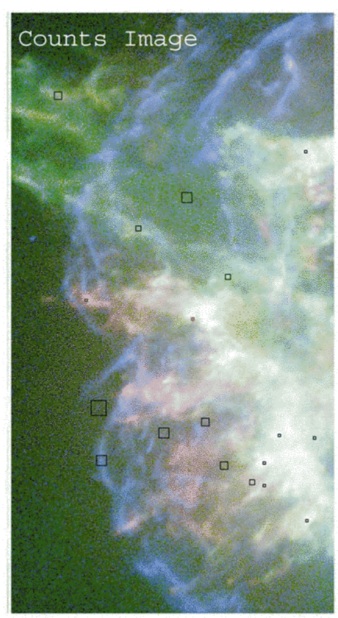
Box Sizes



Depending on the surface brightness (left side), the box sizes vary from 1$''$ to 7$''$ (light to dark, right side).

Box Sizes cont.

This figure depicts
- An RGB image of part of the remnant,
- The extraction boxes used for a selected sample of regions, and
- Extraction boxes as small as 1$''$ (the smallest) and as large as 7$''$ (the largest).



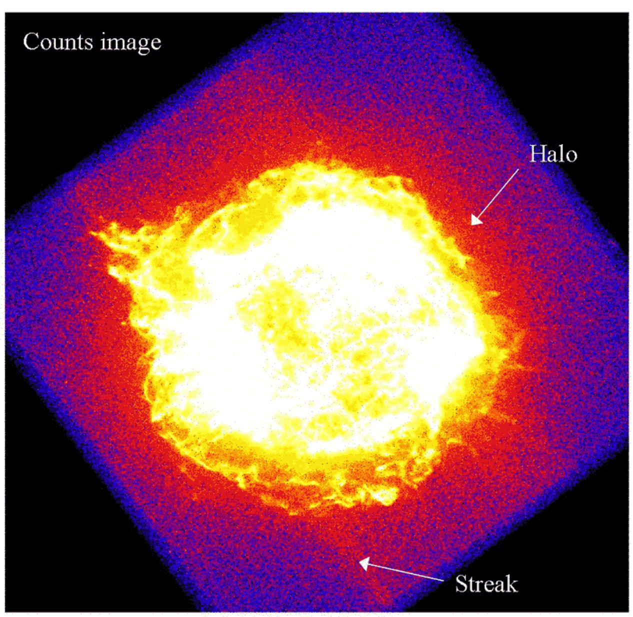
Background

The spectral "background" includes

- "Halo" events from Cas A due to the wings of the point-spread function of the mirrors,
- "Streak" events from Cas A due to the (shutterless) read out of the CCD and
- Events due to the charged particle background.

The analysis of the nonthermal emission used a local background.

Background



ARFs and RMFs

A set of time- and position-dependent effective area (ARF) and energy-to-pulse height redistribution (RMF) files

- were precomputed
- for each epoch
- on a 32 pixel x 32 pixel grid (the same grid used for calibration of the response)
- using the CIAO tools mkarf, mkexpmap and mkacisrmf.

The specific ARF and RMF appropriate for each spectrum was selected using the mean values of the coordinates of the events in the spectral extraction box.

Fitting Algorithm

The fits were performed on several CPUs using

- the spectral-fitting package ISIS (http://space.mit.edu/cxc/isis/) and
- the S-Lang histogram, maplib and pvm modules (http://space.mit.edu/cxc/software/slang/modules/).

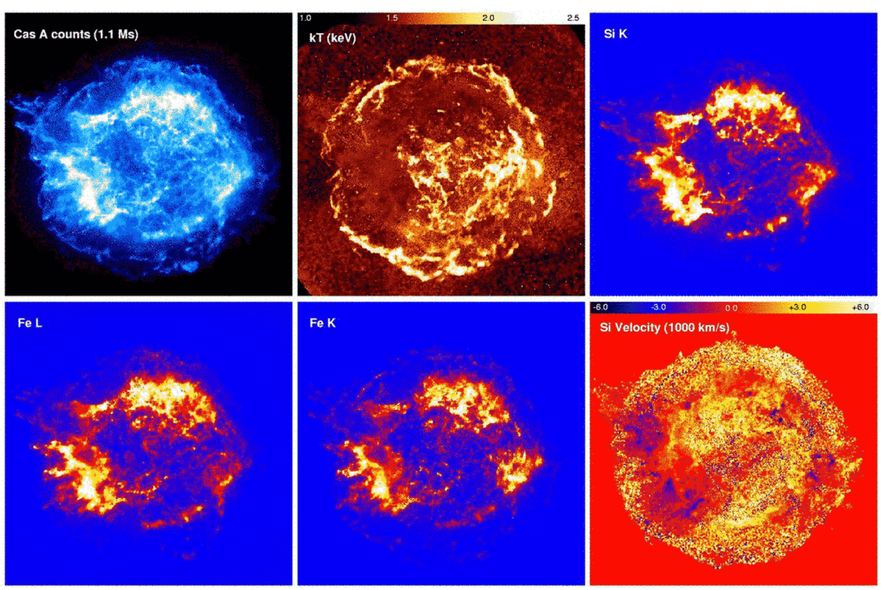
Stage 1 Analysis

Initially, the spectrum for each region was fitted with a phenomenological thermal model that included

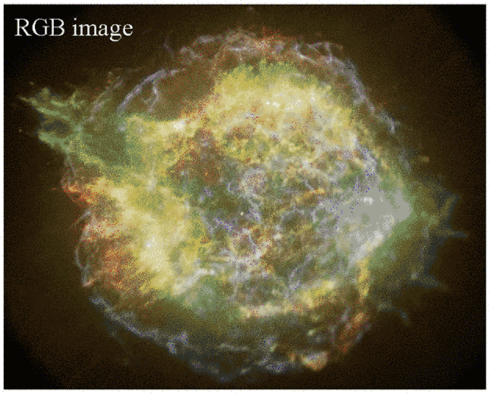
- a bremsstrahlung continuum,
- fifteen Gaussian emission lines [O, Fe L (3), Ne, Mg, Si (3), S (2), Ar, Ca, Ti, Fe K] and
- photoelectric absorption.

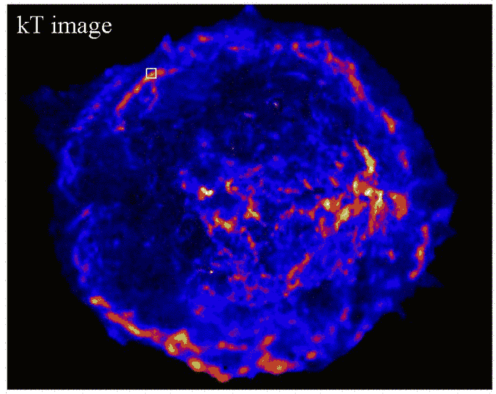
Images of each fitted parameter were created.

Selected Stage 1 Results



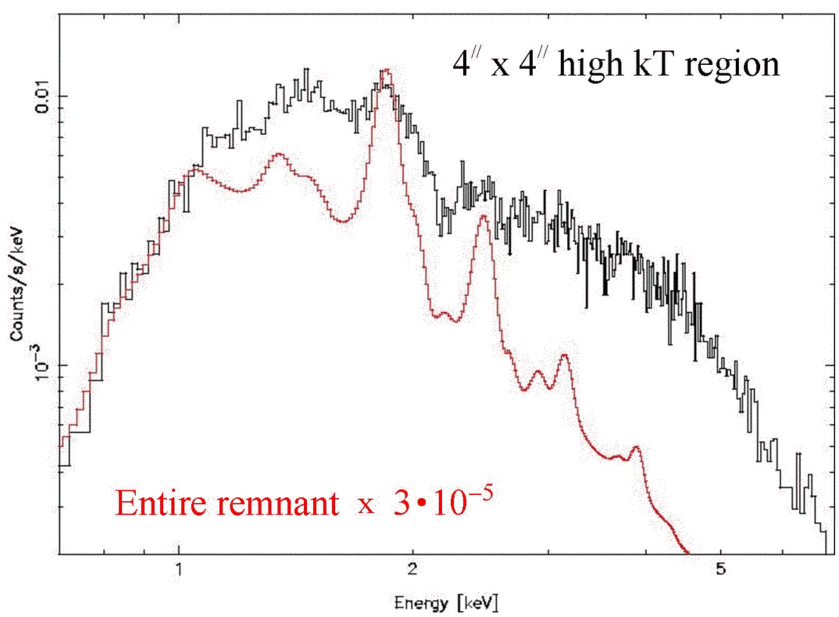
Selected Stage 1 Results cont.





There is a strong correlation between the blue regions in the RGB image (R: 0.5-1.5, G: 1.5-2.5, B: 4.0-6.0 keV) and the regions with a large temperature in the kT image.

Sample High kT Spectrum



Synchrotron radiation

Following Warren et al. (2005), we infer the high kT regions are produced by synchrotron radiation because

- little or no evidence of atomic emission lines would require very low metal abundances and
- the radial profiles are too narrow and peak too close to the forward shock to be consistent with thermal bremsstrahlung emission from shock-heated gas.

Therefore, the 10,857 regions with kT > 2.6 keV were fitted with a synchrotron radiation model.

Nonthermal emission

The synchrotron flux (Houck et al. 2006, in prep.) is based on a nonthermal electron spectrum of the form

$$\frac{dn}{dpc} = A\left(\frac{pc}{\mathrm{GeV}}\right)^{-\Gamma + a\log\left(\frac{pc}{\mathrm{GeV}}\right)} e^{(\mathrm{GeV}-E)/\epsilon}$$

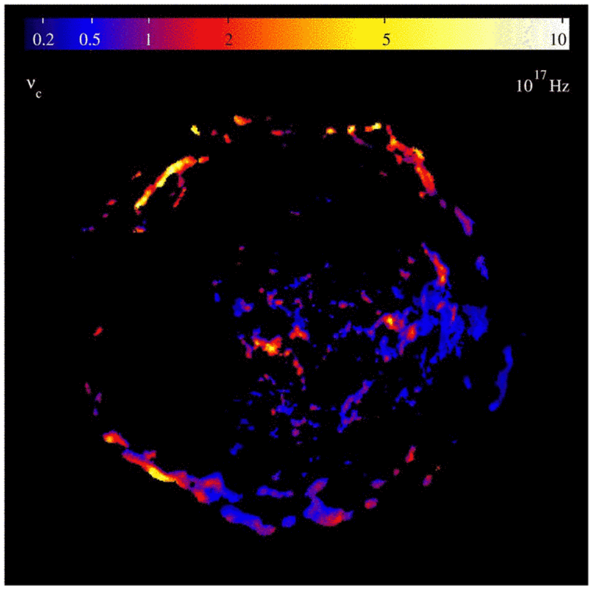
The parameters of the synchrotron model include

- A normalization,
- $\Gamma = 2.54$ (Baars et al. 1977),
- $a = 0.06$ (Jones et al. 2003) and
- A surrogate for the critical frequency

$$\begin{aligned}\nu_{\mathrm{c}} &= \frac{3e}{4\pi m}\gamma^2 B\sin\theta \\ &= 1.26\times 10^{17}\left(\frac{\epsilon}{10\ \mathrm{TeV}}\right)^2\left(\frac{B}{100\ \mu\mathrm{G}}\right)\ \mathrm{Hz}\end{aligned}$$

Synchrotron results

(Stage et al. 2006, in prep.)



Diffusion coefficient

The critical frequency ν_c and the forward shock velocity u_1 can be used to constrain the diffusion coefficient. Since

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

a little algebra yields (c.f. Uchiyama et al. 2003; Lazendic et al. 2004)

$$\frac{\bar{\kappa}}{\kappa_{\rm B}} \leq \frac{9\epsilon_0 mc}{2e^2}\frac{f u_1^2}{\nu_{\rm c}\sin\theta} = 2.1\left(\frac{f}{0.15}\right)\left(\frac{u_1}{5000\ {\rm km\ s^{-1}}}\right)^2\left(\frac{\nu_{\rm c}}{9\times 10^{17}\ {\rm Hz}}\right)^{-1}$$

Electrons diffuse close to the Bohm limit in the regions where $\nu_c = 9 \times 10^{17}$ Hz.

Conclusions

- We performed arcsecond-scale, spatially-resolved, X-ray spectroscopy of Cas A.
- We find that high electron temperatures (and low abundances) seem to be indicative of nonthermal emission.
- When nonthermal-dominated regions are fitted with a synchrotron model, the critical frequency is seen to vary around the outer rim of the remnant.
- The largest critical frequency (9×10^{17} Hz) and a forward shock velocity of 5000 km s^{-1}, suggest that the diffusion coefficient $\kappa < 2.1\ \kappa_B$.
- In these regions, electrons are accelerated about as fast as possible and the maximum electron energy is limited by synchrotron losses.

Caveats

- The critical frequency is sensitive to the unknown shape of the electron spectrum.
- The critical frequency varies from region to region.
- The shock velocity and critical frequency are uncertain.
- The diffusion limits apply only at the cut-off energy of the electron spectrum.
- The compression ratio is unknown.
- The pitch angle distribution may not be isotropic.
- The cut-off energy may not be limited by synchrotron losses.

Synchrotron model

The synchrotron flux spectrum

$$\frac{dF}{dh\nu} = \frac{V_{\rm S}}{4\pi d^2}\frac{\sqrt{3}e^3 B}{2\epsilon_0 mch^2\nu}\int_{\gamma_{\rm min}}^{\gamma_{\rm max}} d\gamma\frac{dn}{d\gamma}\left(\int_0^{\pi} d\theta \sin^2\theta\frac{\nu}{\nu_{\rm c}}\int_{\nu/\nu_{\rm c}}^{\infty} dx K_{5/3}(x)\right),$$

where $dn/d\gamma = (dn/dpc)(dpc/d\gamma)$,

$$\frac{dn}{dpc} = A\left(\frac{pc}{\rm GeV}\right)^{-\Gamma+a\log\left(\frac{pc}{\rm GeV}\right)} e^{({\rm GeV}-E)/\epsilon}, \text{ and}$$

$$\nu_{\rm c} = \frac{3e}{4\pi m}\gamma^2 B\sin\theta = 1.26\times 10^{17}\left(\frac{\epsilon}{10\ {\rm TeV}}\right)^2\left(\frac{B}{100\ \mu{\rm G}}\right)\ {\rm Hz}$$

was fitted to the spectra for the high-kT regions to find $\nu_{\rm c}$.

Diffusion coefficient

Since

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

where

$$-\left(\frac{dE}{dt}\right)_{\rm sync} = \frac{e^4}{6\pi\epsilon_0 m^4 c^5}\,\epsilon^2 B^2 \sin^2\theta$$

$$\left(\frac{dE}{dt}\right)_{\rm acc} = \frac{1}{3}\,\epsilon\left(\frac{\kappa_1}{u_1}+\frac{\kappa_2}{u_2}\right)^{-1}(u_1-u_2) = \frac{f\epsilon u_1^2}{3\bar{\kappa}}$$

Diffusion coefficient cont.

The weighted mean electron diffusion coefficient

$$\bar{\kappa} = \left(\frac{\kappa_1}{u_1} + \frac{\kappa_2}{u_2}\right)\left(\frac{1}{u_1} + \frac{1}{u_2}\right)^{-1}$$

The Bohm diffusion coefficient at $E = \varepsilon$ (i.e. one pitch angle scattering per gyroradius)

$$\kappa_{\mathrm{B}} = \frac{\epsilon}{3eB}$$

The function f of the compression ratio r

$$f = \frac{r-1}{r\,(r+1)}$$

Diffusion coefficient cont.

The upper limit on the mean electron diffusion coefficient

$$\begin{aligned}\frac{\bar{\kappa}}{\kappa_{\mathrm{B}}} &\le \frac{9\epsilon_0 mc}{2e^2}\frac{f u_1^2}{\nu_{\mathrm{c}}\sin\theta} \\ &= 7.49\left(\frac{f}{0.15}\right)\left(\frac{u_1}{10^3\ \mathrm{km\ s^{-1}}}\right)^2\left(\frac{\nu_{\mathrm{c}}}{10^{16}\ \mathrm{Hz}}\right)^{-1} \\ &= 2.1\left(\frac{f}{0.15}\right)\left(\frac{u_1}{5000\ \mathrm{km\ s^{-1}}}\right)^2\left(\frac{\nu_{\mathrm{c}}}{9\times 10^{17}\ \mathrm{Hz}}\right)^{-1}\end{aligned}$$

(c.f. Uchiyama et al. 2003; Lazendic et al. 2004)

Electrons diffuse in the Bohm limit (i.e. are accelerated about as fast as possible), at least in some regions of Cas A.