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Chandra Observations of Tycho's Supernova Remnant

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Abstract. We present a new *Chandra* observation of Tycho's supernova remnant with the Advanced CCD Imaging Spectrometer. Multicolor X-ray imaging reveals new details of the outer shock and ejecta. At energies between 4 and 6 keV, the outline of the outer shock is clearly revealed in X-rays for the first time. The distribution of the emission from lines of Si and Fe are confirmed to have a different morphology from each other, and the Si ejecta are shown to extend to the blast shock at several locations. Characteristic spectra of the outer shock and ejecta are also presented.

Key words. X-rays—supernova remnants—interstellar medium—shocks—Tycho's SNR—SN 1572.

1. Imaging observations

The remnant of SN 1572 in our Galaxy, Tycho's supernova remnant (SNR) is considered to be the prototype for the remnants of Type Ia explosions that occur through runaway thermal instabilities in a white dwarf. It was observed for 50 ks with the superb $0.5''$ resolution mirror on the *Chandra* X-ray Observatory and the moderate resolution Advanced CCD Imaging Spectrometer (ACIS). The linear array of 6 CCD chips comprising ACIS-S was used, with the remnant imaged mostly on the primary spectroscopic chip S3. The western edge falls on neighboring chip S2, and the southern edge is not imaged.

The 0.5–10 keV image obtained by *Chandra* is presented in the first panel of Fig. 1. It shows Tycho's familiar circular shape, but with important new details. First, the outer edge of the remnant is marked by a thin, smooth rim that is visible from the straight northeastern edge through most of the western half. This rim closely matches a similar feature seen at radio wavelengths (Dickel *et al.* 1991). The rim is readily identified with the forward shock of the remnant that is propagating into the interstellar medium. Because the broadband X-ray emission from Tycho's SNR comes mostly from the line-rich reverse-shocked ejecta, the image formed in the nearly line-free continuum energy band between 4 and 6 keV (shown after smoothing in the second panel of Fig. 1) highlights the location of the rim.

The *Chandra* image also reveals in exquisite detail the distribution of the ejecta. It has long been noted that the X-ray emission from Tycho's SNR is clumpy (Seward *et al.* 1983), and a recent, lower spatial resolution, image from the *XMM-Newton* observatory emphasizes this (Decourchelle *et al.* 2001), but the *Chandra* image has

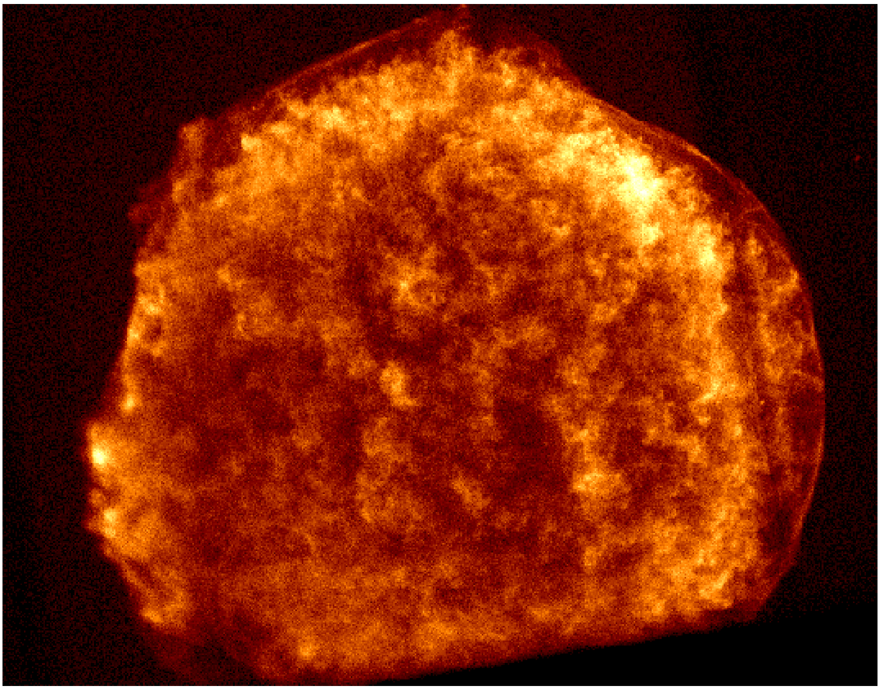

Figure 1(a). Broadband *Chandra* image of Tycho's SNR. The southernmost portion is not imaged.

the highest spatial resolution that has been obtained to date in X-rays. The third panel of Fig. 3 shows an "equivalent width" image of the Si He α blend near 1.86 keV, where the underlying continuum has been subtracted at each point in the Si image, and the ratio formed between the remaining line emission and the continuum. Such an image indicates where the Si element abundance (tracked by the relative strength of the Si line emission) is high. Most of the Si line emission is associated with ejecta because they require element abundances that are enhanced well above the solar values. This implies that the Si ejecta are distributed throughout the remnant, including at many positions near the edge of the remnant at the position of the forward shock.

2. Spectral observations

With *Chandra*'s superb spatial resolution, moderate resolution X-ray spectra can be obtained for any region of the remnant for which there are sufficient numbers of photons. Some spatially resolved spectra of compact regions obtained by *XMM-Newton* were presented by Decourchelle *et al.* (2001). Here we present a small sample of spectra on even smaller spatial scales from *Chandra*.

2.1 *Forward shock*

Chandra is able to obtain the spectrum of the thin rim and provide the first X-ray spectrum of the forward shock in this young, historical remnant. The spectrum shown on the left of Fig. 2 was taken from a portion of the northwest rim that is bright in

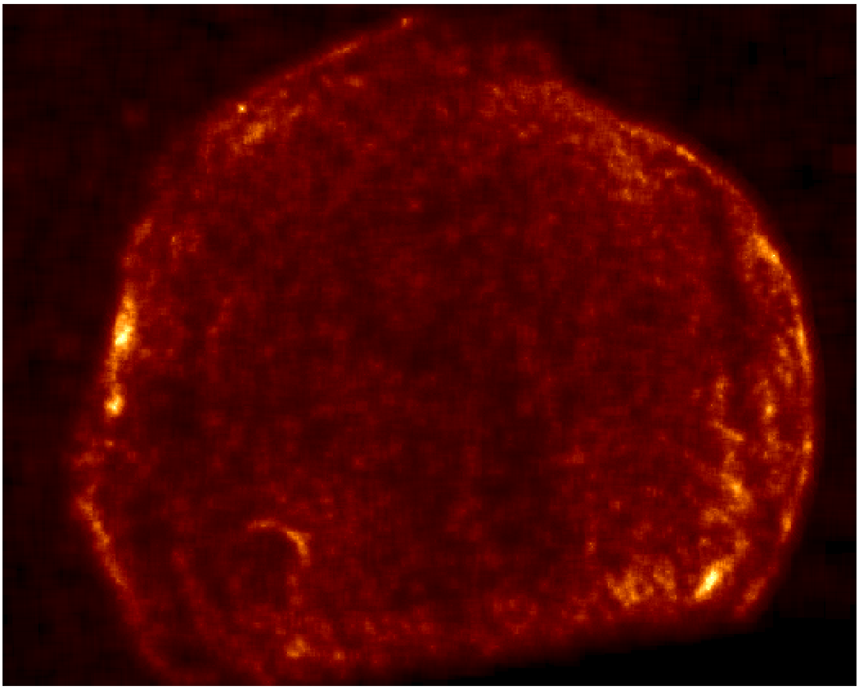

Figure 1(b). Image in the X-ray continuum at energies between 4 and 6 keV.

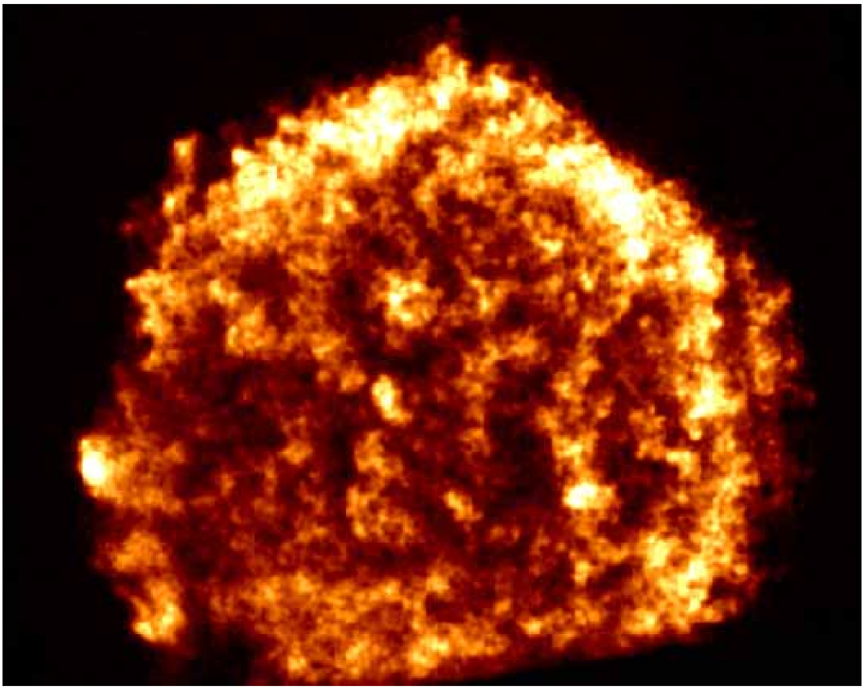

Figure 1(c). Equivalent width image (line to continuum ratio) of the Si He α blend near 1.86 keV.

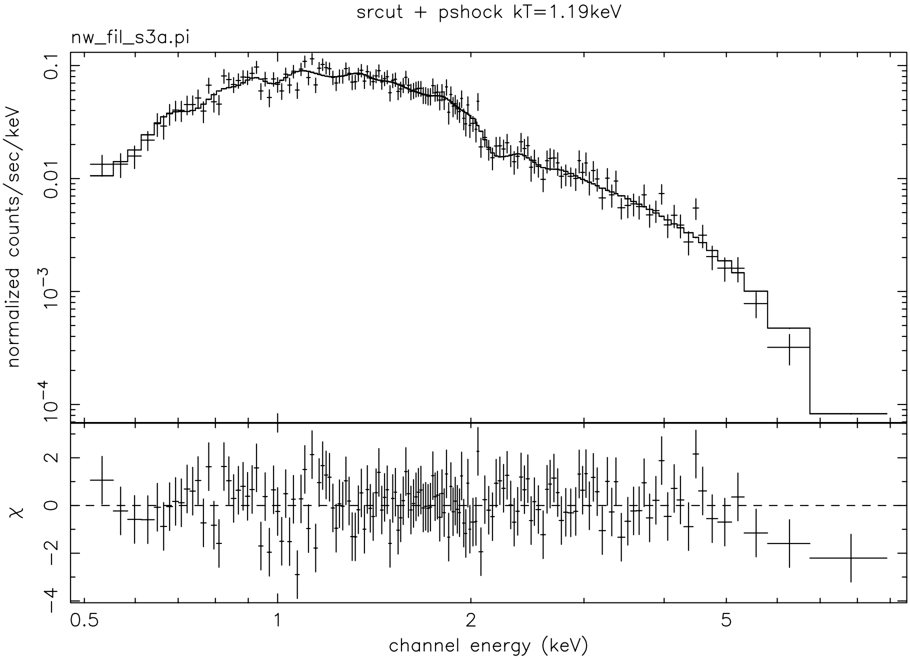

Figure 2(a). Spectrum of portion of rim in northwest. The model combines a cut-off synchrotron spectrum (srcut) and a plane parallel shock with a range of ionization ages (pshock).

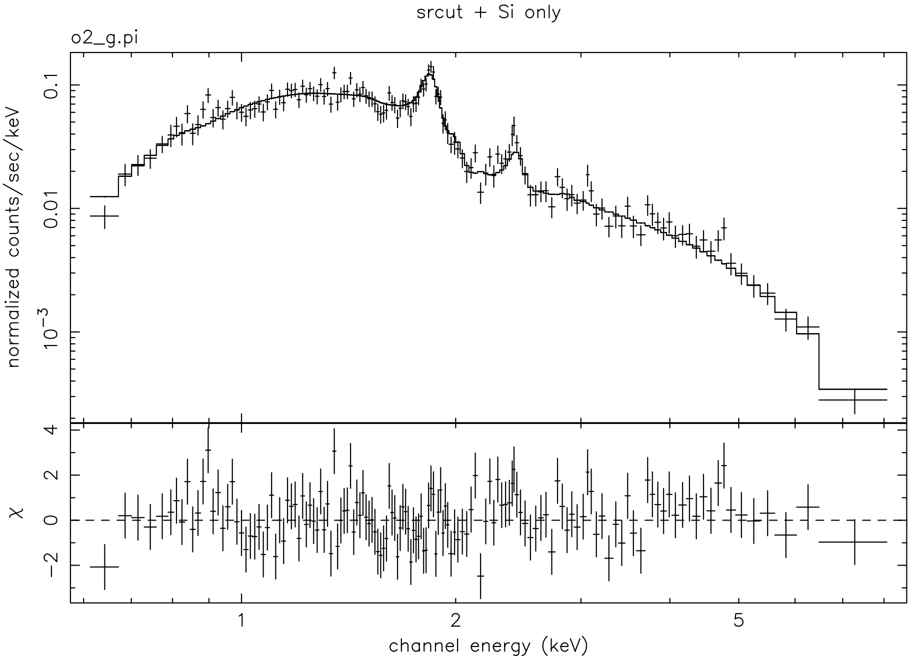

Figure 2(b). Spectrum of portion of rim in west, showing Si and S lines from ejecta.

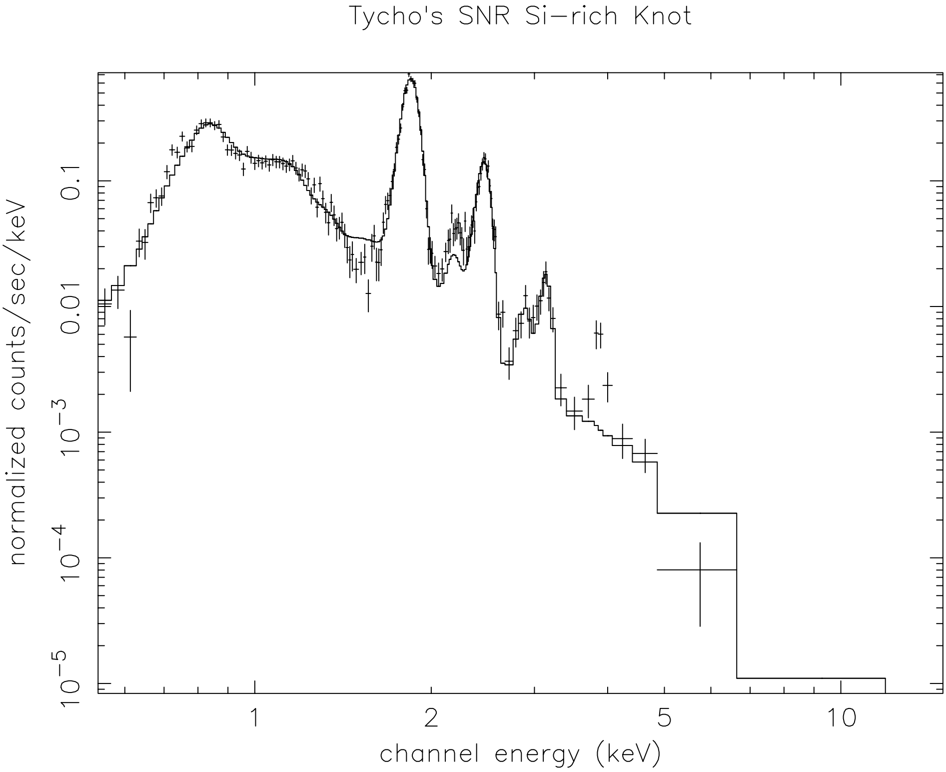

Figure 3(a). Spectrum of the Si-rich knot in the east.

the 4–6 keV continuum. It is nearly devoid of line features, and can be described either by a nonthermal synchrotron spectrum (we used one with an exponential cutoff in the electron distribution function, taking the cutoff frequency from Reynolds & Keohane (1999), and radio spectral indices from Katz-Stone *et al.* 2000), or by a thermal spectrum with very low ionization parameters and a temperature near 2 keV, or by a combination of these.

It is unfortunately not possible to distinguish between thermal and nonthermal scenarios on the basis of the *Chandra* spectra alone. Energy coverage is needed above 10 keV, where the curvatures in the spectra predicted by these models diverge more strongly. Nevertheless, it seems likely that some of the X-ray emission is nonthermal, as there is overall an excellent correspondence between the X-ray and radio outlines at the forward shock (Dickel *et al.* 1991). The nonthermal X-ray emission could come from a population of electrons accelerated to high energies at the shock in the same way as the electrons responsible for the radio emission. Moreover, the radio images show that this northwest arc is also bright in radio emission. Given that there is hard emission detected from the remnant as a whole at energies up to 25–30 keV, it is plausible that a nonthermal emission component coming from the forward shock could be associated with this hard emission.

If this emission is predominately thermal, it shows low electron temperatures compared to the roughly 4600 km/s expansion velocities measured for Tycho's SNR in X-rays (Hughes 2000). The spectra of other regions around the rim are qualitatively

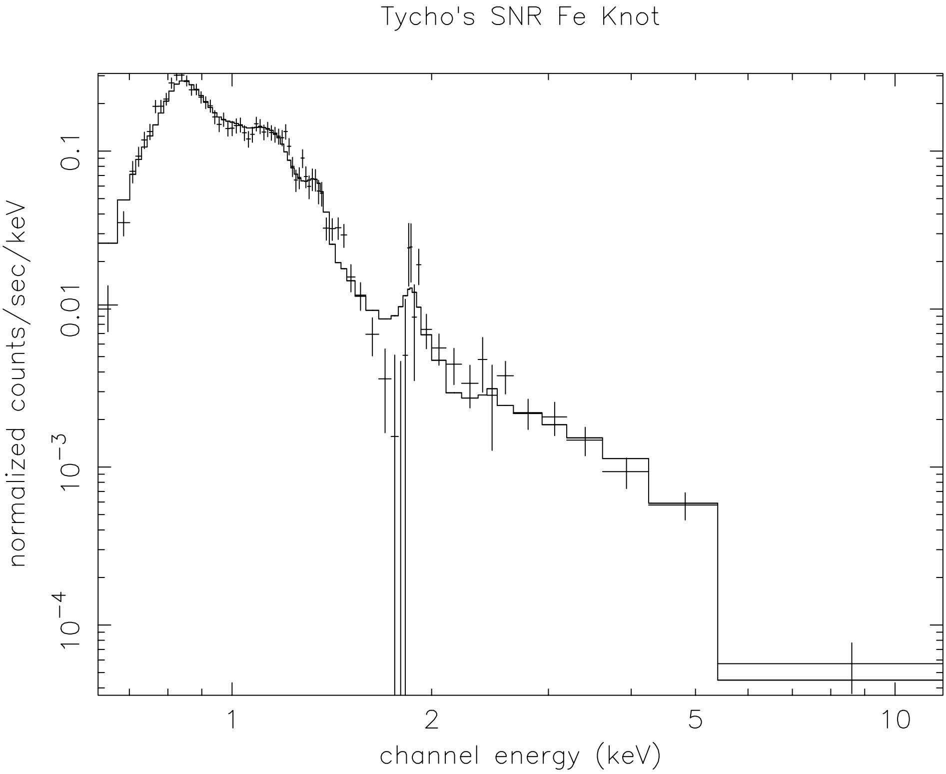

Figure 3(b). Spectrum of the Fe-rich knot in the east.

similar to that of the northwest arc, though they tend to show more Si and S line emission that comes from ejecta that have propagated to the forward shock. Such a spectrum, taken from a portion of the west rim of the remnant, is shown in the right panel of Fig. 2. The fitted model is for a nonthermal component with added thermal emission from Si and S ejecta.

2.2 *Ejecta*

Unlike in Cas A, a remnant with a massive progenitor that exploded via core-collapse, the ejecta in Tycho's SNR are relatively uniform on large scales. *Chandra* does not reveal new structures that were not previously known: the Fe ejecta traced by Fe K emission lies interior to the Si emission due to the thermal structure behind the reverse shock (Decourchelle *et al.* 2001; Hwang & Gotthelf 1997), and Si and Fe knots lie on the eastern edge of the remnant (Vancura *et al.* 1995). *Chandra* can now provide spectra for these regions, however. Fig. 3 shows spectra of the Si and Fe rich knots in the east, with the background taken from the surrounding emission. Clear qualitative differences in the spectra are immediately apparent. The spectrum of the Si-rich knot resembles the broadband spectrum of Tycho's SNR, with strong Si, S, Ar, and Ca emission lines, but shows relatively little Fe, either in the L transitions (to $n = 2$ levels) near 1 keV or in the K transitions (to $n = 1$ levels) near 6.5 keV. The Fe-rich knot shown in the right panel is the opposite. There is a residual Si feature (that is rather sensitive to the background subtraction), but the dominant spectral features are due to the Fe L emission. The spectra are fitted with nonequilibrium ionization thermal models.

3. Summary

Chandra and *XMM-Newton* have inaugurated the era of true spatially resolved X-ray spectroscopy. For supernova remnants like Tycho's SNR, this means the capability to measure, for the first time, the detailed distribution of the ejecta and the spectra of ejecta at different positions in the remnant. It also reveals the spectra at the forward shock, which most likely arise from both nonthermal and thermal emission processes.

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