Chandra Observations of the Bright Eastern Knot of Puppis A


Abstract

We present an observation of the Bright Knot at the eastern edge of the Puppis A supernova remnant with the Chandra ACIS-S detector. The Chandra image clearly shows the "indented" morphology in this region that suggests a blast wave impacting a dense cloud of material, and reveals details of the substructure. Hardness variations are evident from the spectral imaging, and spectral analysis shows a clear temperature gradient increasing from \( \sim 0.3 \) keV at the eastern edge (nearest the blast wave) up to \( \sim 0.6 \) keV toward the interior. The element abundances are at the solar values, consistent with the knot being an inhomogeneity in the interstellar medium. We discuss the results in the context of possible heating by reflected shocks.

Introduction

Puppis A is a “middle-aged” (\( \sim 4000 \) years) remnant and represents one of the best examples of a remnant in the Sedov phase. A ROSAT High Resolution Imager mosaic is shown in Figure 1. It is significantly brighter on its eastern side, indicating a density gradient of a factor of \( \sim 4 \) that increase from southwest to northeast (Petre et al. 1982). Puppis A also features dense knots of interstellar material that are being overrun by shocks. One such example is seen captured by the box in Figure 1, the Bright Eastern Knot. Despite its middle age, Puppis A also shows unmistakable evidence of emission from shocked ejecta, and is one of the “oxygen-rich” class of remnants that includes the ejecta-dominated SNRs Cas A and E0102-72.

Puppis A is a favorite target for X-ray spectral observations (Szymkowiak 1984; Berthiaume et al. 1994; Tamura 1994, to name a few). High resolution X-ray spectra have also been obtained with the Einstein Focal Plane Crystal Spectrometer (Winkler et al. 1981; Flanagan 1990). Prior to the Chandra observation reported here, none of the spectra has provided information on spatial scales smaller than \( \sim 1 \) arcminute. The observation of the Bright Eastern Knot reported here shows spectral variation on much smaller spatial scales.

The Chandra Puppis A Observations

We observed three fields in Puppis A with ACIS-S3: a portion of the eastern shock front (SF), the Bright Eastern Knot (BEK), and the northern knot (NK). The pointing centers, exposures and observation modes are summarized in the table below. This poster reports on one of these observations, that of the Bright Eastern Knot.

<table>
<thead>
<tr>
<th>Region</th>
<th>Observation Date</th>
<th>Pointing Center (J2000)</th>
<th>Exposure (ks)</th>
<th>CCD Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Shock Front</td>
<td>1 Oct 2001</td>
<td>125.842, -42.703</td>
<td>14.9</td>
<td>Faint</td>
</tr>
<tr>
<td>Bright Eastern Knot</td>
<td>4 Nov 2001</td>
<td>126.048, -42.914</td>
<td>10.8</td>
<td>Graded</td>
</tr>
<tr>
<td>Northern Knot</td>
<td>9-10 Mar 2002</td>
<td>125.529, -42.643</td>
<td>19.9</td>
<td>Faint</td>
</tr>
</tbody>
</table>
The $8' \times 8'$ field of view of ACIS-S3 is shown in white in Figure 1, marking the BEK observation within the Puppis A SNR. The Chandra image obtained with ACIS-S3 is shown in Figure 2. The BEK observation was taken in “graded” mode (i.e., the events are graded before telemetry) in order to reduce the risk of telemetry saturation with this bright source. For spectral analysis, background was obtained from a source free region of the chip (toward the east in Figure 2.)

The X-Ray Images

The Chandra image of the Bright Eastern Knot in Figure 2 clearly shows an "indented" morphology. This suggests a blast wave impacting a dense cloud of material and overtaking it on its sides. Images formed in bands corresponding to oxygen emission (soft; energies 0.4–0.7 keV) and Ne emission (medium; energies 0.7–1.2 keV) are shown in Figures 3 and 4, respectively. A tricolor image is shown in Figure 5, combining the two images with a third hard band image (energies $>1.2$ keV). Since the BEK is at or near the eastern boundary, the viewing angle (i.e., edge on) is favorable for seeing the development of emission behind the shock front.

The soft and medium energy images of Figures 3 and 4 illustrate spectral signatures within the region of the Bright Eastern Knot. Of the two bright structures seen in Figure 2, the hook-shaped feature toward the interior is much more prominent in the medium energy band than in the soft band. The bright knot immediately behind the shock front appears to show variation in energy, becoming harder away from the front. This is also seen in the tricolor image of Figure 5.

Spectral Analysis

In order to investigate this variation quantitatively, we selected thirteen extraction regions as illustrated by the boxes in Figure 2. These regions were each 20 pixels $\times$ 40 pixels, (or about $10'' \times 20''$), and were arrayed from the shock front inward, arranged in such a way as to traverse the brightest regions of the two prominent X-ray features. The background was taken from a region to the east, well beyond the shock front.

Although these regions are small, we found that NEI model fits to the spectra were inferior to VPSHOCK model (Borkowski et al. 2001) fits. VPSHOCK is a plane-parallel shock model in which the ionization timescale, $\tau$, which defines the progress of the plasma towards equilibrium, assumes a range of values between upper and lower limits. The need for a VPSHOCK model may signal that the ionization of the plasma is evolving even within the small extraction regions. We set the lower limit on $\tau$ effectively to zero, and fixed the abundances at cosmic values. Cosmic abundances gave reasonably good fits. In those cases where abundance variations could have improved on the fit, we chose not to vary the abundance parameter in order to avoid interplay with the temperature parameter. Thus, the effective parameters were column density $N_H$, electron temperature $T_e$ and (upper) ionization parameter $\tau$. (Note that ACIS absorption was also taken into account in the modeling, but had no free parameters.) The spectrum and best-fit model for the third region from the shock front (near the brightest part of the knot) are shown in Figure 6. For the thirteen regions sampled, typical reduced chi-squares were in the range 1.0–1.7 for these fits.

The temperature results are shown in Figure 7. A clear gradient is seen over 50", starting at $\sim 0.3$ keV at the shock front and climbing to $\sim 0.6$ keV in the interior.
Discussion

The indented morphology of the Bright Eastern Knot and the cosmic abundances found for this region lead us to consider scenarios in which the blast wave overtakes a dense clump of material in the CSM. In the Cygnus Loop, Levenson et al. (2002) see significant temperature changes that support the interpretation that secondary shocks are reflected off a dense interstellar cloud and further heat already-shocked gas. This scenario had been proposed by Hester & Cox (1986), and is illustrated in Figure 8. A blast wave overtaking a dense medium is decelerated ($v_c$ in Figure 8). As explained by Levenson et al. (2002), even though this will not produce such hot plasma, it produces bright X-ray emission. A reflected shock ($v_r$ in the figure) propagates back through the already-shocked medium, compressing and heating it to a higher temperature. Thus, the emission from the reflected shock region is harder than that of the decelerated forward shock.

This describes what we see in with the Chandra observation of the Bright Eastern Knot. The indented shape coinciding with the edge of the shock front suggests retardation at a dense knot, (i.e., a decelerated forward shock). The striking temperature gradient rising behind the shock fits well with the interpretation of a reflected shock heating and compressing the material behind.

Future steps will include examining spectra forward and outside the zone of the reflected shock, estimating the shock velocities within the knot and in the reflected shock region, and estimating the density in the knot.

Acknowledgements

This work was prepared under NASA contract NAS8-01129.

References

Figure 1: ROSAT HRI mosaic of the Puppis A supernova remnant. The box indicates the region of the Bright Eastern Knot that was observed with the S3 chip of Chandra’s ACIS-S detector.

Figure 2: Chandra ACIS-S image of the Bright Eastern Knot. Boxes indicate spectral extraction regions behind the eastern shock front.
Figure 3: Image of the Bright Eastern Knot corresponding to oxygen emission ($\sim$0.4–0.7 keV).

Figure 4: Image of the Bright Eastern Knot corresponding to neon emission ($\sim$0.7–1.2 keV).
Figure 5: Tricolor image combining soft (~0.4–0.7 keV), medium (~0.7–1.2 keV) and hard band (>1.2 keV) images of the Bright Eastern Knot.

Figure 6: The spectrum and best-fit VPSHOCK model for the third region in from the shock front (near the brightest part of the knot in Figure 2). Fits for the thirteen regions shown in Figure 2 were analyzed, and show the temperature gradient of Figure 6. For the spectrum above, the best-fit parameters were: kT=0.43 keV, N_H=.35 cm^{-2}, \tau=6.24\times10^{10} s cm^{-3}.
Figure 7: Analysis of the thirteen regions of Figure 2 indicate a gradient over 50", starting at \( \sim 0.3 \text{ keV} \) at the shock front and climbing to \( \sim 0.6 \text{ keV} \) in the interior.

Figure 8: A blast wave \((v_s)\) encounters a spherical cloud of density \(n_c\) and is decelerated \((v_c)\). A reflected shock forms \((v_r)\), further heating and compressing the material (i.e., the region marked by subscript 2), and increasing the X-ray emission. (Hester & Cox, 1986).