A CHANDRA UPDATE: CHEMICAL COMPOSITION AND SHOCK STRUCTURE IN SUPERNOVA REMNANTS

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ABSTRACT

The combined high-resolution spatial and spectral characteristics of Chandra have given us new insights into the chemical composition and shock structure of supernova remnants. We highlight recent Chandra results on Cas A and 1E0102-72, touching on nucleosynthesis and mixing, as well as shock and velocity structure.

1. INTRODUCTION

This paper is a review of recent Chandra X-ray observations of supernova remnants placed in the context of gamma-ray lines and nucleosynthesis. It will approach the question of chemical composition by focusing on what we can learn about nucleosynthesis in two particular SNRs: Cas A in our own galaxy, and 1E0102-72 in the Small Magellanic Cloud. It touches upon the question of velocity in each, as well as shocks - a term that can be applied to every part of a SNR that emits X-rays. Much of what we learn about Cas A starts with “the particular”: analysis of individual knots within the SNR. But this paper ends with the more general: the “big picture” elements that we are apparent in 1E0102-72. Although much has been done in all wavelengths, the focus here is on a few selected Chandra results.

2. CASSIOPEIA A

Cas A is an ejecta-dominated remnant rich in X-rays believed to be the result of a core-collapse supernova about 320 years ago. Figure 1 shows a color-coded image from the ACIS CCD spectrometer on Chandra. In red are photon energies capturing silicon lines (1.78-2 keV); the blue captures Fe K (6.52-6.95 keV), and the green (4.2 - 6.4 keV) continuum. The continuum image marks the forward shock or blast wave moving out into the surrounding CSM. The line-rich regions indicate matter excited by the reverse shock moving back inward through the ejecta. Note the red ring of silicon ejecta, with blue iron lying outward of it to the southeast. Note also the striking jet-like structure. These give clues to nucleosynthesis and the explosion mechanisms in Cas A.

Fig. 1. The megasecond Chandra observation of Cas A [1]. Note forward shock (green), northeast jet, and SE extension of Fe-dominated ejecta (blue) beyond Si-dominated ejecta (red).

2.1 Nucleosynthesis in Cas A

With Chandra, is it possible to measure the composition of individual knots and determine in which layers of the progenitor the ejecta formed. Hughes et al. [2] found evidence of explosive oxygen-burning in Si-rich knots, and evidence of incomplete or complete explosive Si-burning in Fe-rich knots. As evident in Fig. 1, they also found that Fe-rich material lay outward of Si-rich, indicating an inversion of O-burning and Si-burning products, suggesting more violent large-scale mixing.

Equivalent width images [3] support the conclusion that the Si and Fe K are indeed ejecta, and confirm the notion of overturned ejecta layers. The Si and S maps resemble each other and cleanly delineate the jet. Velocity analysis (see Section 2.4) supports the notion of spatial inversion: Si and S have the same velocity structure, but iron is found to have higher speeds than silicon in the north [4].
The ejecta composition gives us other clues as to explosive nucleosynthesis. Explosive Si burning produces primarily $^{56}$Fe, Si, S, Ar and Ca. However, as the matter expands and cools, alpha-rich freezeout occurs, producing primarily $^{56}$Fe, $^{44}$Ti and $^4$He [5]. This process depends on explosion energy and asymmetry [6][7] and provides an explosion diagnostic. Hwang and Laming [5] detected an ejecta clump of nearly pure Fe, a signature of alpha-rich freezeout.

Further evidence comes from detection of decay products of $^{44}$Ti in Cas A. $^{44}$Ti decays into $^{44}$Sc and thence to $^{44}$Ca. The 1157 keV line of $^{44}$Ca was detected with the COMPTEL telescope on the Compton Gamma-Ray Observatory [8][9]. The 67.9 keV and 78.4 keV lines of $^{44}$Sc were detected by Vink et al. [10] with the Phoswich Detection System (PDS) on board BeppoSAX. These lines were also detected [11] in spectroimaging analysis with the Imager on Board the INTEGRAL Satellite (IBIS) and the INTEGRAL Soft Gamma-Ray Imager (ISGRI). The weighted average of the measurements from COMPTEL, BeppoSAX PDS and ISGRI give an estimated mass [11] of $^{44}$Ti of $1.5\times10^{-4}M_\odot$. This is rather high, suggesting an asymmetric explosion or a more compact progenitor [12][11][10][6]. The intriguing question of explosion asymmetries is explored the next section.

### 2.2 Jets in Cas A

A striking feature in Fig. 1 is the jet-like structure to the northeast. This feature has also been seen in optical observations [13][14]. Fig. 2 highlights the counterjet to the southwest to emphasize the bipolar structure of the supernova remnant.

Although expansion into a cavity is one potential explanation for the NE jet structure, spectral analysis of the knots outlined in Fig. 3 indicate ionization ages and temperatures that are too high to be explained by cavity models [15].

The spectra of knots at the base of the northeast jet structure and elsewhere in the remnant were compared against adiabatic hydrodynamic models [16]: the fitted power law envelope was shallower at the base of the jet, indicating more energy deposition in this polar direction than along the equator [17]. Subsequent analysis [15] of knots in the polar region (Fig. 3) confirm that this structure really is due to a jet from the explosion. However, the jet energy is significantly less than needed to have been a gamma-ray burst or to be compatible with a model [18] of jet-induced explosion [15].

### 2.3 Shock locations in Cas A and Tycho

Inspection of Fig.1 reveals distinct separation between the continuum-dominated forward shock (green) and the ejecta-dominated reverse shock (red). This separation has been measured by examining radial profiles in X-ray continuum, Si lines and radio [19], placing the forward shock at 153$''^{+/-12}$, and the reverse shock at 95$''^{+/-10}$. Comparing the ratio of forward shock to reverse shock distances (~1.5) against adiabatic hydrodynamic models of SNR evolution [16] Gotthelf et al. [19] concluded that the remnant has swept up an amount of circumstellar material about equal to the ejecta mass, and may just be entering the Sedov phase.

The forward and reverse shocks are not always so cleanly separated, as shown in Fig. 4. This Chandra image of the Tycho supernova remnant shows the forward shock in close proximity to the contact discontinuity (defining the extent of the ejecta). This is inconsistent with standard adiabatic hydrodynamic models of SNR expansion, but can be explained by...
cosmic ray acceleration of ions at the forward shock [20].

Fig. 4 The forward shock in Tycho lies in close proximity to the contact discontinuity, suggesting cosmic ray acceleration at the forward shock [20].

The question of particle acceleration in Cas A will be visited in Section 2.5

2.4 Ejecta kinematics of Cas A

X-ray lines have been used to study the kinematics of Cas A for decades. Markert et al. [21] found with the Einstein Focal Plane Crystal Spectrometer data that the northwest region was redshifted with respect to the southeast region with a mean velocity difference of ~2000 km/s, suggesting an inclined ring. This Doppler asymmetry was confirmed with ASCA [22][23]. More recently, Doppler maps based on CCD spectra have been made by Hwang et al. [24] on 4 arcsec scale using Chandra and Willingale et al. [4] on 20 arcsec scale using XMM-Newton. These maps largely confirm the prior X-ray observations but show greater complexity. The Chandra observations indicate measured Si peak velocities of 2000-3000 km/s [24], whereas the XMM measurements for Si are distributed about ~1000 km/s [4]. The XMM data show a broader velocity distribution for red-shifted Fe-K than for Si-K and S-K (which have similar velocity distributions), suggesting a Doppler “inversion” of these elements, analogous to the spatial inversion noted by Hughes et al. [2].

Proper motion measurements constitute another way that Chandra has been used to study the kinematics of Cas A. Proper motions provide transverse velocity, in contrast to line-of-sight velocities which are obtained by Doppler shifts. Prior proper motion studies with Einstein and ROSAT [25][26] found X-ray ejecta to move slower, as a class, than optical and faster than radio knots. This is partially explained by density differences – high density ejecta are decelerated little by the reverse shock and emit at optical wavelengths [27][28][29][30]. Delaney et al. [30] found Si-dominated knots to have a velocity of 3100 km/s, and Fe-dominated knots 3900 km/s, based on measured expansion rate and average radius for these elements. Disagreement between the transverse and line-of-sight velocities might be attributed in part to unequal projection effects caused by nonuniform ejecta.

To conclude this section, consider another technique for obtaining line-of-site velocities with Chandra. The Doppler information obtained with CCD spectra can be complemented by individual line analysis with the dispersed spectrum from the Chandra High Energy Transmission Grating (HETG) Spectrometer. This has the advantage of obtaining energy shifts from resolved rather than blended lines (as in [24]), while avoiding spatial averaging over a variety of features (as in [4]).

Fig. 5 Dispersed HETG spectrum of Cas A. Blurred top panel illustrates sensitivity of long wavelengths to velocity. Two grating orientations and dispersions, as well as + and – orders, help resolve spatial/spectral confusion due to the large angular extent of the source [31].
Fig. 5 shows the HETG spectrum for a 70 ks GTO observation of Cas A [31]. Each dispersed image represents a different energy band. The Si band shows the two different grating orientations and dispersions. These two grating types, and the dual set of positive and negative orders to the sides of the central undispersed zeroth order, help resolve spectral/spatial confusion for extended sources. The top image in Fig. 5 shows smearing, partly caused by the fact that long wavelength images are sensitive to velocity gradients.

Clean velocity diagnostics can be obtained for some individual knots and filaments, as shown in Fig. 6. In that figure, the data (black) and model (red) for helium-like (Si XIII) and hydrogen-like (Si XIV) silicon are clearly blue-shifted with respect to their nominal wavelengths, indicated by blue tick marks above the data. The illustrated profile represents bulk motion, whereas Doppler broadening would smear the Si XIII lines.

The HETG spectrum revealed unambiguous Doppler shifts on selected regions of -2500 (in the southeast) to +4000 km/s (in the northwest) consistent with an expansion rate of 0.19% per year. This is in good agreement with Delaney and Rudnick [29] and DeLaney et al. [30].

2.5 Electron acceleration in Cas A

TeV gamma rays have been detected in Cas A [32][33]. One mechanism by which TeV gamma-rays can be produced is inverse-Compton scattering of Cosmic Microwave Background photons off accelerated electrons. Electrons which are accelerated to TeV energies produce synchrotron radiation at keV energies, making the Chandra megasecond observation a fertile hunting ground for sites of electron acceleration.

Analysis of the Chandra megasecond [plus archival] observations revealed anomalously high temperature regions in thermal Bremsstrahlung fits [34]. Those regions showed little line emission and correlated with the filamentary forward shocks (see Fig. 1), and therefore the emission was identified as more likely to be nonthermal emission from electrons in the shocks.

A synchrotron model accommodating diffusive shock acceleration was applied, incorporating the feature that synchrotron losses will lead to a sharp cutoff. The resultant map of cutoff frequency is given in Fig. 7 [34]. Also shown is an upper limit to the electron diffusion coefficient, estimated from the cutoff frequency and shock velocity. The electron diffusion coefficient constrains the rate of electron acceleration. Stage et al. [34] conclude that electron acceleration to TeV energies is occurring in some regions of the forward shock at nearly the fastest rate theoretically possible, a circumstance that is often assumed when applying diffusive shock theory to SNRs.

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1 It should be noted that the interpretation presented in this section is subject to dispute: Vink and Laming [35] conclude that inverse Compton emission is unlikely to explain detection of TeV emission in Cas A, preferring pion decay.
3. 1E0102-7219

The oxygen-rich supernova remnant 1E0102-7219 in the Small Magellanic Cloud is estimated to be about 1000 years old [36]. Although the X-ray image (Fig. 8) shows a forward shock cleanly distinct from a reverse-shocked ejecta ring (unlike the case with Tycho), there is nonetheless evidence of cosmic ray acceleration at the forward shock. (Hughes et al. [36] found the postshock electron temperature to be significantly lower than expected from proper motion measurements of the blast wave, suggesting shock energy has gone into cosmic ray production.)

Each ring seen in Fig. 9 represents a monochromatic X-ray line, allowing plasma diagnostics with global line ratios. Oxygen lines, marked in red in the figure, are the focus of the discussion that follows. As shown in Fig. 10, ratios of oxygen line fluxes constrain the temperature and ionization state of the plasma. Such ratios eliminate dependence on distance and abundance. The best-fit model for the oxygen plasma can then be used with the measured line flux to estimate the mass of oxygen in the X-ray emitting plasma.

Oxygen is a particularly sensitive indicator of progenitor mass. When compared against nucleosynthesis models by Nomoto et al. [40], the estimated oxygen ejecta mass (~6 solar masses of oxygen, depending on assumptions) is indicative of a massive (~32 solar mass) progenitor [37]. This conclusion was reached independently by Blair et al. [41], who estimated a 25 solar mass progenitor based on optical and UV data.
Fig. 10 Line ratios of the brightest H-like and He-like lines of oxygen are used to constrain the temperature and ionization state of the oxygen plasma [37].

3.2 Ionization structure and the reverse shock in 1E0102-72

Close inspection of the HETG spectrum of Fig. 9 indicates systematic differences in relative ring diameter. Two sections of the spectrum are expanded below in Fig. 11 for comparison. The bright H-like O\(\text{VIII}\) Ly\(\alpha\) ring at the right is clearly larger than the O\(\text{VII}\) rings at the left, even though these X-ray lines all originate from the same element. These rings delineate the emitting region: For oxygen, the more highly ionized state lies outward of the less ionized state.

![O VII triplet and O VIII Ly\(\alpha\)](image)

Fig. 11 H-like oxygen ring (right) is larger than He-like oxygen rings (left) [37].

This holds true for all the elements – the bright lines of hydrogen-like ions are found at larger ring diameter than helium-like ions. This can be explained by progressive ionization due to passage of the reverse shock – the reverse shock interacts with the outer ejecta prior to encountering the inner ejecta, so the outer ejecta is more highly ionized. Ring diameter would then be expected to correlate with ionization timescale.

The result of applying a simple model to test this hypothesis given in Fig. 12. On one axis is plotted the ionization timescale for peak emissivity of bright X-ray lines produced by a plane-parallel shock propagating in an isothermal, uniformly-mixed plasma. On the other axis is the measured ring radius of each of the lines from the HETG spectrum. The data are interleaved in the order expected from a homogeneous plasma and an inward propagating shock: no separation of elements is required.

![Measured ring size vs ionization timescale](image)

Fig. 12. Measured ring size vs ionization timescale assuming a simple isothermal model. (This does not reflect actual conditions in the SNR, but illustrates the correlation.) [37]

3.3 Doppler Map of 1E0102-72

Comparison of the undispersed image of E0102-72 (Fig. 8) with the individual rings of the HETG spectrum shows distortions in the ring structure that are attributable to bulk Doppler shifts of order ~1000 km/s. The techniques for determining Doppler velocities of limited regions of the remnant are analogous to those illustrated in Fig. 6.

In order to produce a more detailed Doppler map, the HETG data for one X-ray line were modeled with a data cube representing two spatial dimensions and one wavelength dimension corresponding to discrete red- and blue-shifted components. The source model data cube was forward-folded to create modeled dispersed images, and was adjusted to obtain the best fit [37]. The best-fit data cube was used to create the color-coded image in Fig. 13.
A striking feature seen in the Doppler map of Fig. 13 is the spatial separation of the red and blue shifted velocity components. Such a separation might occur with a cylindrical or elongated distribution viewed off-axis. A non-spherical distribution like this could arise in the core-collapse process, or through the influence of the CSM. A plausible scenario might involve expansion into a surrounding medium preconditioned by wind from the precursor.

4. SUMMARY

This paper focuses on two supernova remnants, Cas A in our galaxy, and 1E0102-72 in the Small Magellanic Cloud, to illustrate new insights into chemical composition and shock structure enabled by Chandra. In detailed Chandra images of Cas A, we see evidence for violent large-scale mixing in overturned ejecta from O-burning and Si-burning layers. We see the signature of alpha-rich freezeout, consistent with prior detections of $^{56}$Ti. These provide insights into explosive nucleosynthesis, just as the bipolar structure of the jets hints at asymmetry in the explosion. Nucleosynthesis in 1E0102-72 is approached in a different way: Plasma diagnostics are used to estimate the oxygen ejecta mass, pointing toward a massive progenitor. Asymmetry is also evident in 1E0102-72, as suggested by its spatially distinct red and blue shifted components, possibly indicating interaction with a nonuniform CSM.

As for shock structure, the Chandra images allow us to clearly distinguish the forward shock and reverse-shocked ejecta. The forward shock is often believed to be the site of cosmic ray acceleration. Evidence for this is seen in the proximity of Tycho’s forward shock to its ejecta. Particle acceleration is also likely occurring in 1E0102-72, and is now mapped by Chandra in Cas A. The reverse shock is generally believed to be the mechanism that lights up the ejecta, giving rise to thermal spectra rich in X-ray lines. The line-emitting regions are individually distinguishable in the dispersed high-resolution HETG spectrum of 1E0102-72, and show progressive ionization of the plasma – a compelling picture of the reverse shock in action.

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6. REFERENCES