Locating the CSM Emission within the Type Ia Supernova Remnant N103B

Benson T. Guest1,2,3, William P. Blair4, Kazimierz J. Borkowski5, Parviz Ghavamian6, Sean P. Hendrick7, Knox S. Long8,9, Robert Petre2, John C. Raymond10, Armin Rest8, Ravi Sankrit8, Ivo R. Seitenzahl11, and Brian J. Williams2

1 Department of Astronomy, University of Maryland, College Park, MD 20742, USA; bguest1@umd.edu
2 NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
3 Center for Research and Exploration in Space Science and Technology, NASA/GSFC, Greenbelt, MD 20771, USA
4 The William H. Miller III Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218, USA
5 North Carolina State University, Raleigh, NC 27607, USA
6 Department of Physics, Astronomy and Geosciences, Towson University, Towson, MD 21252, USA
7 Millersville University, Millersville, PA 17551, USA
8 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
9 Eureka Scientific, Inc., 2452 Delmer Street, Suite 1, Oakland, CA 94602-3017, USA
10 Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
11 University of New South Wales, Australian Defence Force Academy, Canberra, ACT 2600, Australia

Received 2021 September 13; revised 2021 December 16; accepted 2021 December 25; published 2022 February 25

Abstract

We present results from deep Chandra observations of the young Type Ia supernova remnant (SNR) 0509–68.7, also known as N103B, located in the Large Magellanic Cloud (LMC). The remnant displays an asymmetry in brightness, with the western hemisphere appearing significantly brighter than the eastern one. Previous multiwavelength observations have attributed the difference to a density gradient and suggested origins in circumstellar material, drawing similarities to Kepler’s SNR. We apply a clustering technique combined with traditional imaging analysis to spatially locate various emission components within the remnant. We find that O and Mg emission is strongest along the blast wave, and coincides with Spitzer observations of dust emission and optical emission from the nonradiative shocks. The abundances of O and Mg in these regions are enhanced relative to the average LMC abundances and appear as a distinct spatial distribution compared to the ejecta products, supporting the interpretation based on a circumstellar medium. We also find that the spatial distribution of Cr is identical to that of Fe in the remnant, and does not coincide at all with the O and Mg emission.

Unified Astronomy Thesaurus concepts: Supernova remnants (1667); Interstellar medium (847)

1. Introduction

A Type Ia supernova is the result of a thermonuclear detonation of a white dwarf star at the Chandrasekhar mass. The path to explosion is likely to have multiple origins. The simple picture is either a single degenerate system where a white dwarf accumulates mass from a nondegenerate companion star, or the merger of two white dwarfs in a double degenerate system. Each of these paths has numerous theoretical subtypes and possibilities (e.g., Maoz et al. 2014). Proving which origin a particular remnant has, and determining the dominant Type Ia channel, remains an active area of investigation. One approach is to look for evidence of interaction with a circumstellar medium (CSM) remaining from mass outflow from the binary system prior to the explosion. This might be expected from a single degenerate progenitor system, but not from a double degenerate one. Another method is through analysis of ejecta abundances and structure.

Here we present results from a deep Chandra observation of the supernova remnant (SNR) 0509–68.7, often labeled as N103B, located in the Large Magellanic Cloud (LMC). Spitzer observations (Williams et al. 2014) suggest that the remnant is interacting with a dense CSM ($n_0 \approx 10$ cm$^{-3}$), drawing similarities to Kepler’s SNR, which shows comparable densities (Blair et al. 2007; Williams et al. 2012). Li et al. (2021) used Multi-Unit Spectroscopic Explorer (MUSE) observations obtained with the Very Large Telescope (VLT) to study the dense knots of CSM, finding densities $\geq 10,000$ cm$^{-3}$. Currently, these are the only two known Type Ia remnants that show dense CSM interaction hundreds of years after the explosion.

N103B spans 30$''$ in diameter, which corresponds to 7.2 pc at the LMC distance of 50 kpc. Hughes et al. (1995) used X-ray observations with ASCA to identify N103B as the remnant of a Type Ia supernova, overturning a previous assumption of a core-collapse progenitor by Chu & Kennicutt (1988) based on the proximity to an H II region and the OB association NGC1850. The Type Ia identifier has been supported by numerous further studies (Lewis et al. 2003; Lopez et al. 2011; Yang et al. 2013; Yamaguchi et al. 2014). The star formation history surrounding N103B was studied by Badenes et al. (2009), who found vigorous star formation in the recent past, suggesting the progenitor or its companion may have been relatively massive. A light echo from the supernova was found by Rest et al. (2005), from which they derived an age of $\approx 860$ yr. Further support for this young age is provided by expansion measurements from Chandra observations separated by 17 yr (Williams et al. 2018), where the overall average shock velocity is found to be in excess of 4000 km s$^{-1}$, and measurements of Balmer-dominated shocks with average velocity of $2070 \pm 60$ km s$^{-1}$ by Ghavamian et al. (2017). The Balmer-dominated filaments are in locations with significant preshock neutral hydrogen. The difference between
Kepler and N103B rather than ejecta. With such obvious similarities between
the remnant the areas with pronounced O and Mg emission and
they are spatially coincident with CSM emission,
utilizing a data clustering algorithm to identify the location of
(Williams et al. 2014) developed an X-ray analysis technique
to the N103B (red) and Tycho (blue). The N103B and Kepler spectra have been scaled up to align the 2.1–2.2 keV continuum with that of the Tycho spectrum.

Table 1

| ObsID | Year | Exposure Time (ks) |
|-------|------|--------------------|
| 125‡  | 1999* | 36.7               |
| 3810‡ | 2003* | 29.7               |
| 18018 | 2017  | 39.5               |
| 18019 | 2017  | 59.3               |
| 18020 | 2017  | 27.2               |
| 19921 | 2017  | 16.9               |
| 19922 | 2017  | 41.4               |
| 19923 | 2017  | 58.3               |
| 20042 | 2017  | 19.8               |
| 20053 | 2017  | 11.2               |
| 20058 | 2017  | 43.8               |
| 20067 | 2017  | 29.7               |
| 20074 | 2017  | 31.2               |
| 20085 | 2017  | 14.9               |

Note. *The 1999 and 2003 observations are not used in the spectral analysis.

The Balmer line velocity and measured X-ray proper motion velocity is consistent with measurements of other SNRs, e.g., Tycho with Balmer line velocities of \(\sim 2000–3000 \text{ km s}^{-1}\) and X-ray proper motion velocities of \(\sim 4000–6000 \text{ km s}^{-1}\) (Ghavamian et al. 2001; Williams et al. 2017).

The X-ray spectrum of N103B, shown in Figure 1, shows strong lines from the “standard” elements typically seen in Type Ia SNR spectra (Si, S, Ar, Ca, Fe). Lines from O and Mg are seen as well. Whether the O and Mg result primarily from the CSM or from unburnt ejecta remains an open question. Burkey et al. (2013) developed an X-ray analysis technique utilizing a data clustering algorithm to identify the location of components characteristic of CSM and ejecta within a remnant. They applied their technique to Kepler’s SNR, locating within the remnant the areas with pronounced O and Mg emission and showing that they are spatially coincident with CSM emission, rather than ejecta. With such obvious similarities between Kepler and N103B (Williams et al. 2014), an obvious question to ask is whether the O and Mg seen in N103B originate from the CSM or the ejecta.

We apply a modified version of this technique to the N103B observations, combined with traditional imaging and spectroscopic analysis. We show that the most significant O and Mg emission appears to follow a distinct distribution, spatially separated from the emission dominated by intermediate-mass ejecta. Additionally, we show that the distribution of the O and Mg emission morphologically correlates with emission from the CSM observed at other wavelengths.

2. Observations

N103B was observed early in the Chandra mission for \(\sim 40 \text{ ks}\) (PI: G. Garmire) in 1999. On 2003 February 3 a \(\sim 30 \text{ ks}\) observation (PI: S. Portegies Zwart) had N103B fall within the field of view; however, the target was an LMC star cluster, and N103B is far off-axis, where Chandra’s spatial resolution is substantially lower. As a result, these data are not used for spectral analysis in this work. A 400 ks program (PI: B. Williams) was split into 12 segments and completed between 2017 March 20 and June 1. The details are given in Table 1 with all observations using the ACIS-S array, and the 1999 and 2017 observations positioning N103B on Chandra’s optical axis pointing of the S3 chip. The data were processed using the CIAO version 4.11 chandra_repro script and CalDB version 4.8.3. For spectral modeling we fit the observations simultaneously, finding strong residuals from the 1999 and 2003 observations compared to the 2017 observations in the soft \(\lesssim 1 \text{ keV}\) range. There appears to be a systematic difference between the epochs, where the best-fit models overpredict the flux in the early observations. A future study may investigate this difference to determine whether there is conclusive evidence for intrinsic brightening of the source, but we consider the most likely source of this discrepancy is the build up of contaminant on the ACIS detectors, which primarily affects the softer energies (Marshall et al. 2004). For the purposes of this paper, we will therefore use only the 2017 observations for spectral
fitting, which provide the largest sample of self-consistent data, and exclude those from the earlier epochs to avoid unnecessarily increasing our systematic errors. We retain the early observations for our imaging analysis.

3. Methods and Results

3.1. Comparison with Other Young Type Ia SNRs

We extracted a global spectrum from a circle encompassing the ∼30″ diameter remnant, with a background taken from an annulus of 27″–35″ radius surrounding the remnant. The spectrum is plotted in black in Figure 1 along with Chandra spectra of Kepler’s SNR and Tycho’s SNR in red and blue, respectively. The spectra are arbitrarily scaled to be normalized at 2 keV for display purposes.

These three remnants are all the result of Type Ia supernovae in the last ∼1000 yr, yet their spectra differ substantially. N103B and Kepler show remarkable agreement, particularly compared to Tycho. Kepler and N103B are roughly an order of magnitude brighter at 1 keV than Tycho is, relative to the rest of the spectrum. This is similar to the situation in the mid-IR, where Spitzer observations of these remnants also show that Kepler and N103B are much more luminous than Tycho (Blair et al. 2007; Williams et al. 2013, 2014), despite being at a comparable evolutionary state. The simplest explanation of the major differences in the IR and X-ray spectra from these remnants is that Kepler’s SNR and N103B are expanding into very dense material, two orders of magnitude greater than Tycho. The subtle differences in Ar and Ca line emission at ∼3.1 and ∼3.9 keV, respectively, and the energy centroid of the Fe Kα line at ∼6.5 keV are explained by the age of N103B being roughly twice that of Kepler, leading to differences in ionization equilibrium.

3.2. Narrowband Images

We constructed a single image by reprojecting the 14 observations to a common axis and merging the event files using the CIAO script merge_obs. From this, we extracted narrowband images using the CIAO tool dmcopy with 1″ binning for each of the band energies listed in Table 2. In Figure 2 (left) we show spatial separation of O and Mg emission from the Fe L-shell lines as well. Chandra’s spectral resolution is not sufficient to disentangle O from Fe L-shell lines, but for the purposes of this paper, we simply label the region “O.”

3.3. Equivalent Width Images

We then constructed equivalent width images (EWIs), which highlight line emission relative to the strength of the continuum using the procedure outlined in Hwang et al. (2000) and Winkler et al. (2014). From the merged event file we created narrowband images binned with 1″ pixels for each of the energy bands listed in Table 2. We estimate the continuum by linearly interpolating between the normalized low- and high-energy bands to calculate a predicted continuum image. We then subtracted this continuum image from the normalized line image and the excess was then divided by the predicted continuum, and the resulting image was smoothed with a 2 pixel Gaussian.

Figure 3 shows the resulting EW images. The O and Mg images show enhancements that appear as a ring tracing the edge of the remnant with minimal contributions from the center. The Si image shows enhancement filling the remnant; however, it is most significant in a horseshoe morphology with lesser enhancement in the south extending to the center. The Si Lyα line is strong enough to create a similar image and shows stronger enhancement in the fainter eastern half. S, Ar, and Ca all show most significant enhancement on the eastern side with...
pockets filling the remnant. There is a notable hole in each image which coincides with the pocket of interior enhancement seen in the Mg image as the inward extension of the contour in the north. The Fe Kα image shows prominent emission filling the remnant, with the brightest emission located to the southwest of the remnant center.

To examine the correlation between elements we extracted spectra from the contours highlighting the enhanced regions shown in Figure 3 and compared to the spectra from a circle encompassing the full remnant with the contour regions excluded (Figures 4 and 5). To highlight the differences between the spectra rather than the overall brightness, scaling was changed where necessary in order to align the spectra at the level of the 2.1–2.2 keV continuum.

Primary differences occur in the soft ∼0.5–1.5 keV range. The regions that show enhanced O lines correlate with the enhanced Mg regions such that each shows prominent lines of the other. The heavier intermediate-mass elements—Si through Ca—do not show any obvious correlation with enhancement of other elements, nor does the Fe L-shell or Kα emission.

We attempted to create an EWI for Cr (∼5.6 keV), but the line emission is insufficient to create an image with meaningful statistics given the minimal apparent line enhancement over the dim continuum emission at 5 keV. However, comparing images filtered by the line energies of Cr and Fe from Table 2 (Figure 6), we find a remarkable spatial agreement between the two, with both displaying prominent emission from a bright knot in the southwest interior.

3.4. Clustering

A method to identify and spatially separate emission from different origins was developed by Burkey et al. (2013). Their work focused on separating emission from shocked CSM from that arising from ejecta. We build on this method and introduce the adaptive binning algorithm Contbin (Sanders 2006).12

12 https://github.com/jeremysanders/contbin/
This routine takes an input image and, starting from the brightest pixel, builds up a region following the surface brightness until the number of counts it contains meets a specified value. The result is a set of puzzle-piece-like regions that cover an image while all containing a specified minimum number of counts. The input image we used was a reprojected and merged collection of all 14 Chandra observations binned to 0.25 pixels and spanning 0.3–10 keV. The CONTIN routine was then run on this image to create regions containing \( \sim 7000 \) photon counts. This produced over 200 regions (Figure 7).

For each region, we summed the number of photon counts belonging to narrowband energies (Table 2). The selected bands are O, Mg, Si, S, and the \( \sim 1 \) keV Fe complex. We normalized the number of counts in each band by the band...
energy width, and divided by a normalized associated continuum band to remove inherent bias due to continuum brightness. These continuum bands are the O low, Mg high, Si high, and S high bands. The counts for the Si and S lines were summed to produce one value, and the Fe complex line used the Si and S high bands summed for its continuum ratio. For each region we calculated a 4D vector containing the O, Mg, Fe peak, and Si plus S ratios. Further processing was done by normalizing each vector component relative to the mean. We applied the \textit{kmeans} clustering algorithm (Lloyd 1982) to the set of vectors for a set number of clusters from 2 to 10. The number of clusters represents the number of components we wish to identify. The algorithm attempts to minimize the sum of the 4D distances from the cluster center to each region associated with that cluster.

We extracted spectra from each region with background taken from an annulus surrounding the remnant. These individual regions display varying characteristics (Figure 8). We merged the spectra from regions identified as belonging to a common cluster using the CIAO routine \textit{combine_spectra}, and examined by eye the combined spectrum (Figure 9) to search for the presence of O and Mg line features. We value a cluster at 1 if both O and Mg features are seen, 0.75 if one is seen and it is unclear whether the other is present, 0.5 if only one is present, and 0 if neither feature is visible. Results are displayed in Figure 10.

In agreement with the EWIs, the regions bordering the edge of the remnant show prominent O and Mg line features while the interior regions, particularly for cluster numbers greater than six, show either Mg and no O or neither of the two features. An additional result was the identification of clusters that contained strong line wings belonging to additional Si and S transitions, such as the Si Ly$\alpha$ line at 2.01 keV. See Figure 11 for an example.
We find that for larger numbers of clusters, spectra continue to separate into groups with similar characteristics. With seven or more clusters, the O and Mg features are found in spectra only derived from regions bordering the edge of the remnant, with the most prominent features found on the western side. The strongest Lyα lines of Si and S are found from a band that runs from the bottom of the remnant toward the center.

We investigated these regions in more detail by fitting each spectrum of the merged ten clusters with a VNEI model (see Section 4) over the limited energy range 1.7–2.8 keV, a range that covers the Si and S lines. Williams et al. (2017) showed that with strong emission lines from Si and S, this range is sufficient to constrain the ionization state of the plasma. The ionization timescale is mapped in Figure 12. The ionization timescale correlates inversely with brightness, with the bright western half of the remnant displaying a shorter timescale than the fainter eastern half. This is counterintuitive since the ionization timescale should correlate with electron density and brightness. We investigated the constraints on the ionization fits with the error contour plots in Figure 13. The ionization timescale is not tightly constrained for the fainter central region, yet it favors a longer timescale and lower temperature. The large difference in brightness between the eastern half of the remnant and the region we identify with the longest ionization timescale likely plays a role. The excess continuum emission unaccounted for in our one-component model may effectively weaken the appearance of the Lyα line, leading to a systematically shorter timescale in the brighter regions. Despite these uncertainties, this region with a long ionization timescale is spatially coincident with a similar region identified as an inner ring by the component analysis of Yamaguchi et al. (2021), supporting the presence of substructure within the remnant.
4. Spectral Modeling

The EWIs presented in Figure 3 highlight regions where the line emission is the strongest relative to the continuum. The spectra extracted from contours surrounding the brightest line-emitting regions shown in Figures 4 and 5 show that the EWIs represent real features in the underlying spectra. We cannot immediately attribute areas of line brightness revealed by the EWIs to locally enhanced abundances in these regions. It is possible that they may result from the effect of ionization timescale and plasma temperature in enhancing the emission. To examine the underlying abundances in more detail, we fit the spectra with an absorbed multicomponent nonequilibrium ionization plasma model VNEI (Borkowski et al. 2001). The absorption from the Milky Way is modeled by a \( \text{Tbabs} \) model with Wilms abundances (Wilms et al. 2000) fixed to \( 6 \times 10^{20} \text{ cm}^{-2} \) (Dickey & Lockman 1990) and a free-to-vary LMC component modeled with \( \text{Tbvarabs} \) with the LMC average abundances from Dopita et al. (2019). We fix one VNEI component with the average LMC abundances, a second component is composed of only the intermediate-mass elements Si, S, Ar, and Ca present and allowed to vary, and a third component is Fe-only. We process the observations individually, creating response files and background for each.

Comparing the best-fit models from the EWI contour spectra for Mg, we find enhanced O and Mg from the outer ring contours compared to the interior. The best-fit models from the Mg enhanced contours and the remnant with these regions excluded are listed in Table 3, and the spectra are shown in Figure 14.

5. Multiwavelength Observations

The multiwavelength picture of N103B reveals a complex structure (Figure 15). At X-ray energies, the remnant shows a
circular morphology with the western half appearing significantly brighter than the east. At infrared wavelengths, only the western half is visible, with the deconvolved Spitzer 24 μm image revealing a limb and knot structure (Williams et al. 2014). This same structure is seen at high spatial resolution in narrowband Hubble images from Li et al. (2017) and Blair et al. (2020), where it is clear the bright emission knots, visible in F502N [O III], F673N [S II], and F164N [Fe II], arise from
The integrated X-ray spectrum of N103B shows prominent lines from Si, S, Ar, Ca, and Fe. In addition, there are weaker lines from O and Mg. We have used spatial analysis using EWIs and the clustering technique described above to show that the O and Mg lines are found predominantly from a shell bordering the edge of the remnant while the intermediate-mass elements fill the interior.

Despite the overwhelming difference in brightness of the remnant from west to east, the distribution of ejecta products does not reflect any obvious east–west asymmetries in the EWIs. Using multiplicative scaling to align spectra by their continuum level. The clustering analysis reveals a distinct separation in the location of the strongest O and Mg emission compared to the ejecta products, in agreement with EWIs and the clustering technique described above to show that the O and Mg lines are found predominantly from a shell bordering the edge of the remnant while the intermediate-mass elements fill the interior.

This is in agreement with the results of Yamaguchi et al. (2021), who used a component analysis technique to reveal similar structure. Where our results differ is in our abundance measurement of the O- and Mg-rich emission. Allowing these parameters to vary, we find enhanced O and Mg from regions spatially coincident with the Spitzer emission (Williams et al. 2014) and from the outer blast wave of the remnant. The uncertainties on the abundances are likely much larger than the

### Table 3

| Component | Parameter | Contours | Excluded |
|-----------|-----------|----------|----------|
| Galactic  | n_H (10^{22}cm^{-2}) | 0.06 (frozen) | 0.06 (frozen) |
| LMC       | n_H (10^{22}cm^{-2}) | 0.15 (0.147–0.153) | 0.265 (0.26–0.27) |
| CSM       | kT (keV) | 0.9 (0.89–0.91) | 0.834 (0.830–0.835) |
|           | O       | 1.9 (1.87–1.95) | 0.63 (0.61–0.66) |
|           | Mg      | 0.69 (0.68–0.71) | 0.42 (0.41–0.43) |
|           | Tau     | 1.56E+11 | 1.84E+11 |
|           | (s cm^{-3}) | (1.54E11–1.58E11) | (1.81E11–1.88E11) |
|           | Norm    | 5.54E-03 | 9.72E-03 |
|           | (cm^{-3}) | (5.51E-3–5.55E-3) | (9.70E-3–9.74E-3) |
| Ejecta    | kT (keV) | 3.32 (3.30–3.39) | 4.6 (4.5–5.0) |
|           | Si      | 2.58 (2.55–2.61) | 2.07 (2.01–2.15) |
|           | S       | 2.43 (2.39–2.48) | 1.99 (1.95–2.05) |
|           | Ar      | 2.74 (2.62–2.89) | 2.05 (1.95–2.16) |
|           | Ca      | 4.5 (4.29–4.76) | 3.43 (3.3–3.62) |
|           | Tau     | 5.32E+10 | 5.01E+10 |
|           | (s cm^{-3}) | (5.24E10–5.40E10) | (4.94E10–5.07E10) |
|           | Redshift | –3.80E-03 | –2.72E-03 |
|           | (cm^{-3}) | (–3.395E–3.38E-3) | (–2.77E–3.26E-3) |
|           | Norm    | 2.40E-03 | 2.78E-03 |
|           | (cm^{-3}) | (2.39E-3–2.52E-3) | (2.72E-3–2.83E-3) |
| Fe        | kT (keV) | 7.4 (6.8–8.1) | 10.9 (10.7–11.4) |
|           | Tau     | 7.03E+10 | 5.66E+10 |
|           | (s cm^{-3}) | (6.86E10–7.20E10) | (5.59E10–5.69E10) |
|           | Redshift | –3.80E-03 | –2.72E-03 |
|           | (cm^{-3}) | (1.26E-3–1.29E-3) | (2.06E-3–2.14E-3) |
|           | Norm    | 1.26E-03 | 2.10E-03 |
|           | (cm^{-3}) | (1.23E-3–1.29E-3) | (2.06E-3–2.14E-3) |
|           | χ_{df}(ν) | 1.787 (2718) | 2.346 (2874) |

**Note.** The spectra are plotted in Figure 14. See the text for details.

**Figure 14.** Spectral models from Table 3. The black spectrum is from the Mg contours and the red spectrum is from the rest of the remnant. The spectra have been merged for display purposes and the red spectrum has scaled down by a factor of 3 to avoid overlap. The model derived from simultaneously fitting the individual observations is overlaid on the merged spectrum. We have highlighted in gray the O and Mg bands that show prominence in the contour spectrum.
values calculated from the data statistics in XSpec, and the spectrum shows residuals at low energies, suggesting that these abundances should be taken rather as upper limits. However, the presence and coincidence of the strongest O and Mg line emission with the dust emission as seen in the 24 μm Spitzer image, and the clear difference in spatial distribution compared to the ejecta products, drives our argument that the remnant is encountering CSM, likely originating from mass loss from the progenitor system.

The absence of N lines observable with Chandra means we are unable to contrast the N to O ratios from the bright radiative knot studied in Blair et al. (2020). Future high-spectral-resolution X-ray observations with XRISM and ATHENA will clarify the extent to which Fe L-shell lines are present in the “O” band, and will allow a more accurate determination of the elemental abundances. Finally, IR observations with the James Webb Space Telescope at a spatial resolution comparable to that of Chandra will allow for a much more detailed morphological comparison between the emissions from dust and from gas in the remnant.

7. Conclusions

Using both EWIs and a clustering technique, we have found spatial differences in the distribution of O and Mg and the intermediate-mass ejecta elements. We have confirmed that these regions are spectroscopically different as well. The O and Mg EWI and clustering images are morphologically similar to the Spitzer mid-IR emission from warm dust and the Hα emission from nonradiative shocks, both of which arise from the interaction of the forward shock with the dense CSM, providing some evidence that the O and Mg seen in the X-rays also arise from a CSM origin.

The ejecta element EWIs show no preference for the bright western limb in terms of line enhancement, suggesting the difference in appearance is due to the enhanced density into which the remnant is expanding. The exception is the emissions in the Cr and Fe Kα lines, which are primarily concentrated in a knot of emission in the southwest. The O and Mg EWIs and spectra extracted from the most prominent regions contained therein present evidence of enhanced O and Mg relative to the average LMC abundances, suggesting the remnant is sweeping into CSM that originates from mass loss from the presupernova system.

Support for this work was provided by NASA through Chandra General Observer Program Grant SAO G06-17064. B.G acknowledges the material is based upon work supported by NASA under award number 80GSCF21M0002. WPB acknowledges partial support from the JHU Center for Astrophysical Sciences during the time of this work. We thank the referee for their careful reading of the paper which improved its quality and clarity.
Figure 17. Image of N103B showing the reverse shock as traced by MUSE [Fe XIV] 5303 Å line emission (Seitenzahl et al. 2019) in red, and the Chandra O EWI and narrowband line image in green and blue, respectively.

Figure 16. Contours from the Mg EWI overlaid on the deconvolved Spitzer 24 μm image.
ORCID iDs

Benson T. Guest © https://orcid.org/0000-0003-4078-0251
William P. Blair © https://orcid.org/0000-0003-2379-6518
Kazimierz J. Borkowski © https://orcid.org/0000-0002-2614-1106
Parviz Ghavamian © https://orcid.org/0000-0002-9886-0839
Knox S. Long © https://orcid.org/0000-0002-4134-864X
Robert Petre © https://orcid.org/0000-0003-3850-2041
John C. Raymond © https://orcid.org/0000-0002-7868-1622
Armin Rest © https://orcid.org/0000-0002-5044-2988
Ivo R. Seitenzahl © https://orcid.org/0000-0003-2063-381X

References

Badenes, C., Harris, J., Zaritsky, D., & Prieto, J. L. 2009, ApJ, 700, 727
Blair, W. P., Ghavamian, P., Long, K. S., et al. 2007, ApJ, 662, 998
Blair, W. P., Ghavamian, P., Raymond, J. C., et al. 2020, ApJ, 902, 153
Borkowski, K. J., Lyerly, W. J., & Reynolds, S. P. 2001, ApJ, 548, 820
Burkey, M. T., Reynolds, S. P., Borkowski, K. J., & Blondin, J. M. 2013, ApJ, 764, 63
Chu, Y.-H., & Kennicutt, R. C. J. 1988, AJ, 96, 1874
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Dopita, M. A., Seitenzahl, I. R., Sutherland, R. S., et al. 2019, AJ, 157, 50

Ghavamian, P., Raymond, J., Smith, R. C., & Hartigan, P. 2001, ApJ, 547, 995
Ghavamian, P., Seitenzahl, I. R., Vogt, F. P. A., et al. 2017, ApJ, 847, 122
Hughes, J. P., Hayashi, I., Helfand, D., et al. 1995, ApJL, 444, L81
Hwang, U., Holt, S. S., & Petre, R. 2000, ApJL, 537, L119
Lewis, K. T., Burrows, D. N., Hughes, J. P., et al. 2003, ApJ, 582, 770
Li, C.-J., Chu, Y.-H., Gruendl, R. A., et al. 2017, ApJ, 836, 85
Li, C.-J., Chu, Y.-H., Raymond, J. C., et al. 2021, ApJ, 923, 141
Lloyd, S. 1982, ITIT, 28, 129
Lopez, L. A., Ramirez-Ruiz, E., Huppenkothen, D., Badenes, C., & Pooley, D. A. 2011, ApJ, 732, 114
Maoz, D., Mannucci, F., & Nelan, G. 2014, ARA&A, 52, 107
Marshall, H. L., Tennant, A., Grant, C. E., et al. 2004, Proc. SPIE, 5165, 497
Rest, A., Suntzeff, N. B., Olsen, K., et al. 2005, Natur, 438, 1132
Sanders, J. S. 2006, MNRAS, 371, 829
Seitenzahl, I. R., Ghavamian, P., Laming, J. M., & Vogt, F. P. A. 2019, Phil. Trans. R. Soc. A, 377, 20190033
Williams, B. J., Blair, W. P., Borkowski, K. J., et al. 2018, ApJL, 865, L13
Williams, B. J., Borkowski, K. J., Ghavamian, P., et al. 2013, ApJ, 770, 129
Williams, B. J., Borkowski, K. J., Reynolds, S. P., et al. 2012, ApJ, 755, 3
Williams, B. J., Borkowski, K. J., Reynolds, S. P., et al. 2014, ApJ, 790, 139
Williams, B. J., Coyle, N. M., Yamaguchi, H., et al. 2017, ApJ, 842, 28
Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914
Winkler, P. F., Williams, B. J., Reynolds, S. P., et al. 2014, ApJL, 781, 65
Yamaguchi, H., Acero, F., Li, C.-J., & Chu, Y.-H. 2021, ApJL, 910, L24
Yamaguchi, H., Badenes, C., Petre, R., et al. 2014, ApJL, 785, L27
Yang, X. J., Tsunemi, H., Lu, F. J., et al. 2013, ApJ, 766, 44