SPATIALLY RESOLVED CHANDRA SPECTROSCOPY OF THE LARGE MAGELLANIC CLOUD SUPERNOVA REMNANT N132D

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ABSTRACT

We perform detailed spectroscopy of the X-ray brightest supernova remnant (SNR) in the Large Magellanic Cloud (LMC), N132D, using *Chandra* archival observations. By analyzing the spectra of the entire well-defined rim, we determine the mean abundances for O, Ne, Mg, Si, S and Fe for the local LMC environment. We find evidence of enhanced O on the north-western and S on the north-eastern blast wave. By analyzing spectra interior to the remnant, we confirm the presence of a Si-rich relatively hot plasma ($\gtrsim 1.5 \text{ keV}$) that is also responsible for the Fe K emission. *Chandra* images show that the Fe K emission is distributed throughout the interior of the southern half of the remnant but does not extend out to the blast wave. We estimate the progenitor mass to be $15 \pm 5M_{\odot}$ using abundance ratios in different regions that collectively cover a large fraction of the remnant, as well as from the radius of the forward shock compared with models of an explosion in a cavity created by stellar winds. We fit ionizing and recombining plasma models to the Fe K emission and find that the current data cannot distinguish between the two, hence the origin of the high-temperature plasma remains uncertain. Our analysis is consistent with N132D being the result of a core-collapse supernova in a cavity created by its intermediate mass progenitor.

Keywords: supernova:individual (N132D), Xrays:individual (N132D), ISM:supernova remnants, plasmas, shock waves, ISM:abundances.

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1. INTRODUCTION

Magellanic cloud supernova remnant (MCSNR) J0525-6938 (commonly referred to as N132D, following the catalog by Henize 1956) is the X-ray-brightest SNR in the Large Magellanic Cloud (LMC; Long & Helfand 1979) with an Xray luminosity of $L_X \sim 3 \times 10^{37} \text{ erg s}^{-1}$ (Maggi et al. 2016)¹. It was first classified as a core-collapse supernova (CCSN) by Westerlund & Mathewson (1966), and has been subsequently studied in great detail over the last few decades (Favata et al. 1997; Xiao & Chen 2008; Bamba et al. 2018; Law et al. 2020). Based on optical observations, it has been classified as an Oxygen-rich remnant (Danziger & Dennefeld 1976; Lasker 1978, 1980), thought to have exploded inside a low density cavity in the interstellar medium (ISM, Hughes 1987). Sutherland & Dopita (1995) discuss the origin of this cavity, which might have formed due to a wind bubble mechanism common to Wolf-Rayet stars (Dwarkadas 2007). It has been proposed by Blair et al. (2000) that this remnant might be the outcome of a Type Ib supernova (core collapse) and is believed to be roughly 2500 yr old (Morse et al. 1995; Hughes et al. 1998; Chen et al. 2003; Vogt & Dopita 2011; Law et al. 2020).

There are several characteristics of this remnant that make it a useful laboratory to study SNRs interacting with molecular clouds. Analysis of NuSTAR (Nuclear Spectroscopic Telescope Array) and Suzaku observations of N132D by Bamba et al. (2018) reinforces the claim by Dickel & Milne (1995) that this remnant is in the transition stage from a young to a middle-aged remnant. The integrated radio luminosity of N132D at 1 Ghz is 50 per cent of Cas A, an SNR which is $\sim 5.5 \times$ smaller in diameter than N132D (Dickel & Milne 1995). High Energy Spectroscopic System (H.E.S.S.) observations of N132D classify this radio loud SNR as one of the strongest emitters of γ rays in the LMC (H.E.S.S. Collaboration et al. 2015; Ackermann et al. 2016). It has been estimated N132D has converted up to 17% of its explosion energy into accelerating cosmic rays (H.E.S.S. Collaboration et al. 2015). N132D is also the brightest SNR amongst all the known SNRs in the 1-100 GeV band (Acero et al. 2016). There is evidence for active star formation in the vicinity of N132D, as observed in the H α images from Magellanic Cloud Emission-Line Survey (MCELS, Smith & MCELS Team 1999; Smith et al. 2004), however, no young stellar objects (YSOs) have been detected in the molecular cloud interacting with the SNR (Desai et al. 2010; see also, Danziger & Dennefeld 1976).

Chandra X-ray Observatory (Chandra) observations (Borkowski et al. 2007) reveal a well-structured rim running along the southern part of the remnant (see Figure 1).

This well-defined rim is associated with dense molecular clouds in this direction (Banas et al. 1997; Sano et al. 2015) and is also present in the infrared (IR) observations of dust continuum emission in N132D taken by Spitzer (Williams et al. 2006). Using IR data from Spitzer and Herschel Space Observatory (Lakićević et al. 2015), it has been proposed that the X-ray emitting hot plasma has destroyed almost half of the dust grains in the remnant (Tappe et al. 2006, 2012; Seok et al. 2013; Dopita et al. 2018; Zhu et al. 2019). The Xray emission also shows a bright arc-shaped structure close to the outermost shell in the south and south-east that may be attributed to the reverse shock encountering the ejecta or face-on filaments produced by the forward shock interacting with density enhancements in the surrounding medium. Towards the north, there are filament-like structures protruding outwards that are relatively faint in X-rays as compared to the rest of the remnant. Given that these structures are at the edge of the H I cloud (Kim et al. 2003) that encompasses the remnant (Maggi et al. 2016, see their Figure 12), they may have resulted as a consequence of strong shocks breaking out of the cavity into the ambient ISM.

Although N132D is the brightest SNR in the LMC in Xray, a full spectral analysis of the archival *Chandra* data (Borkowski et al. 2007) have not yet been performed. In this work, we carry out a spatially-resolved analysis of the well-defined rim as well as several interesting regions in the interior of the remnant that collectively cover around onethird of the remnant in projection. We assume the distance to N132D to be 50 kpc in all calculations hereafter (Clementini et al. 2003; Pietrzyński et al. 2013, 2019). At this distance, 1'' = 0.24 pc. We describe the data reduction and processing in Section 2, and source and background models used for spectral analysis of all the regions in Section 3. Section 4 gives the resulting fits. We discuss the results in Section 5, and summarize our analysis in Section 6.

2. X-RAY DATA AND REDUCTION

We use X-ray observations of SNR N132D obtained with the S3 chip in *Chandra's* Advanced Charged Couple Device (CCD) Imaging Spectrometer (ACIS-S) detector array (Bautz et al. 1998). N132D was observed for 89ks by *Chandra* (Borkowski et al. 2007) in three ACIS-S observations in the Very Faint mode (see Table 1). These X-ray observations showed the pc-scale substructure in the previously-known roughly elliptical shape ($\sim 14.8 \times 10.9$ pc) in exquisite detail. We find no flaring in the data after examining the light curves of the observations. However, the X-ray data suffer from pileup in certain regions (Ballet 1999; Davis 2001). We show a map of the pileup in the remnant in Appendix A. For certain bright areas in the regions in the interior where pileup is greater than 10 per cent, we exclude them from the fit. We utilize the X-ray analysis package *Chandra* Interactive

¹ The quoted X-ray luminosity is uncorrected for LMC absorption.

Table 1. Chandra ACIS-S observation log of SNR N132D.

ObsID	Observation Date	Exposure (ks)	RA	Dec	Roll
05532	Jan 09, 2006	44.59	81.2595°	-69.6437°	330.2°
07259	Jan 10, 2006	24.85	81.2595°	-69.6437°	330.2°
07266	Jan 15, 2006	19.90	81.2595°	-69.6437°	330.2°

Analysis of Observations (CIAO version 4.9, Fruscione et al. 2006) and *Chandra* Calibration Database (CALDB, version 4.7.3, Graessle et al. 2007). We use Xspec version 12.9.1k (Arnaud 1996) to perform X-ray spectroscopy in various regions in the remnant. The line emission data is taken from AtomDB version 3.0.7 (Foster et al. 2013) whereas the non-equilibrium ionization (NEI) models come from NEI version 3.0.4. We use the cosmic abundance set by Wilms et al. (2000) as the baseline abundance level for all our analysis.

3. SPECTRAL ANALYSIS

We first analyze the well-defined rim of SNR N132D to get a picture of emission from the forward shock. We number the rim regions r1 - r19 in the clockwise direction, as we show in Figure 1. We also identify and analyze two "blobs" (labeled b1 and b2) which are likely protruding ahead of the forward shock. We then search the entire remnant for regions that show possibly enhanced abundances of one or more elements, through visual inspections of narrow band images centered on line features of O, Ne, Mg, Si, S and Fe (see Appendix A), as well as hardness ratio images in the soft (0.3 - 0.9 keV), medium (0.9 - 2 keV), and hard (2 - 7 keV)bands. We select interior regions e1, f1, f2, f3, f4, f5 and f6 for further study (see Sections 3.2.2 and 3.2.3 for additional details). We note that regions f2, f3 and f6 contain bright areas in projection that are significantly affected by pileup, as shown in Figure A.1. We exclude such areas when performing X-ray spectroscopy on these regions. Table 2 lists the classification of each region together with the location of its center and area; following subsections describe the background and source models we use to fit the background and source spectra, respectively.

3.1. Background Model

The background region we select is a 1.62' square located at RA = 05:24:36.963, Dec = -69:37:05.68 at a distance of 2.74' from the remnant. We do not subtract the background spectrum from each source spectrum, rather, we model it separately because of the low number of counts at energies > 2.5 keV. With low counts, the subtraction of Poisson distributions results in a distribution which is non-Poissonian and far from Gaussian; in addition, the number of counts af-

negion	Bootanon	10.1	200	
r1	Rim	5:24:57.753	-69:37:56.60	
r2	Rim	5:24:55.700	-69:38:03.86	
r3	Rim	5:24:54.851	-69:38:15.55	
r4	Rim	5:24:54.186	-69:38:30.42	
r5	Rim	5:24:53.824	-69:38:40.57	
r6	Rim	5:24:53.929	-69:38:46.91	
r7	Rim	5:24:54.364	-69:38:54.15	
r8	Rim	5:24:55.145	-69:39:04.67	
r9	Rim	5:24:56.799	-69:39:16.15	
r10	Rim	5:25:01.193	-69:39:21.65	
r11	Rim	5:25:05.082	-69:39:19.87	
r12	Rim	5:25:06.968	-69:39:13.36	
r13	Rim	5:25:08.805	-69:39:03.01	
1.4	D.	5 35 10 341	60 20 47 50	

Region

Location

r8	Rim	5:24:55.145	-69:39:04.67	1.81
r9	Rim	5:24:56.799	-69:39:16.15	6.37
r10	Rim	5:25:01.193	-69:39:21.65	6.29
r11	Rim	5:25:05.082	-69:39:19.87	1.48
r12	Rim	5:25:06.968	-69:39:13.36	2.22
r13	Rim	5:25:08.805	-69:39:03.01	2.10
r14	Rim	5:25:10.241	-69:38:47.50	2.73
r15	Rim	5:25:11.173	-69:38:36.08	1.01
r16	Rim	5:25:12.741	-69:38:23.41	2.75
r17	Rim	5:25:14.211	-69:38:09.52	1.29
r18	Rim	5:25:13.631	-69:38:02.10	2.17
r19	Rim	5:25:11.931	-69:37:55.47	1.91
b1	Blob	5:24:54.730	-69:39:05.84	4.05
b2	Blob	5:25:00.428	-69:39:26.84	6.36
e1	Interior	5:25:07.105	-69:38:15.80	1.21
f1	Interior	5:24:58.031	-69:38:42.24	17.51
f2	Interior	5:25:03.585	-69:38:44.65	11.20
f3	Interior	5:25:07.744	-69:38:56.73	14.49
f4	Interior	5:25:04.716	-69:38:48.14	13.74
f5	Interior	5:25:01.888	-69:39:06.96	12.23
f6	Interior	5:25:04.575	-69:39:11.08	10.16

ter subtraction can be negative (see, for example, van Dyk et al. 2001; Garofali et al. 2017).

We differentiate the background model into sky (imaged through the X-ray optics) and detector (not imaged through the optics) components. For the detector background model, we analyze the so-called "stowed" background data in the Very Faint mode to construct a spectral model for the S3 CCD, similar to the approach used for the ACIS-I CCDs by Bartalucci et al. (2014). We download the background data set acis7D2005-09-01bgstow_ctiN0002.fits from the CALDB. We then run acis_process_events to populate the TDETX and TDETY columns. After copying over the status column from acis7D2005-09-01bgstow_ctiN0002.fits to the processed file (since acis_process_events zeroed the status col-

Area (pc²)

1.93 2.84 2.51

2.99

0.96

0.82

Table 2. Classification of all regions (shown in Figure 1) we study in this work. The RA and Dec coordinates mark the centers of each region. All the rim regions have at least 3500 X-ray photon counts within 0.3 - 7.0 keV.

Dec

RA

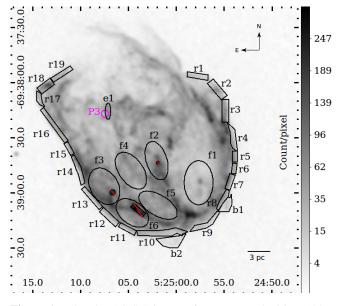


Figure 1. *Chandra* ACIS-S image of counts per pixel in N132D in the 0.35 - 7.0 keV band with *x* and *y* axes showing the Right Ascension (RA) and Declination (Dec), respectively. One pixel is 0.5'', where 1'' = 0.24 pc. The grey scale has been inverted so that darker shade corresponds to higher counts. All regions studied in this work are indicated by black polygons with labels. r1 - r19 are the rim regions and b1 - b2 are the two likely protrusions beyond the blast wave. In the interior, we study regions e1 (which has enriched abundances of O, Ne, Mg, Si and Fe) and f1 - f6 (where weak Fe K emission is detected). Black areas with a red strikethrough line within regions f2, f3 and f6 are the bright patches affected by pileup which are excluded from the spectroscopic analysis. P3 is an O-rich region found in optical studies of N132D by Morse et al. (1996, 1995); Blair et al. (2000).

umn), we apply the CIAO tool reproject events, using ObsID 05332 as the match file to project the background events to the sky. We extract the detector background from the same region as used for the sky background (see below), and generate a weighted RMF using a WMAP in TDET coordinates. The detector background model consists of a broken powerlaw (bkn2pow) to represent most of the spectrum from 0.3-11.0keV, with a broad Gaussian to account for the high energy ACIS-S3 background continuum. We include Gaussian lines for the instrumental fluorescence lines (Al K α , Si K α , Au M complex, Ni K α , and Au L β). We initially adopt the line energies from Bearden (1967), subsequently thawing the line energy for Si K α , the Au M complex, Ni K α and the Au L β complex. We also that the line width for Au M and Au L β complexes. Once a good fit is found, we freeze all of the parameters, and thaw a multiplicative const parameter (initially frozen at 1.0) which provides an overall normalization scaling.

The sky model consists of an absorption (tbabs) plus two thermal plasma <code>apec</code> ($\sim 0.2 \, keV$ and $\sim 0.8 \, keV$) components and a powerlaw. The 0.19 keV <code>apec</code> model primarily

represents emission from the local hot bubble (LHB) and the 0.77 keV model represents other Galactic and LMC emission along the line of sight and the Galactic Halo (Snowden et al. 1998, 2008). There may be emission from the LHB that contributes to the emission we model with the 0.77 keV plasma model and there may be emission from the Halo that contributes to the emission we model with the 0.19 keV plasma model (Snowden et al. 1997; Kuntz & Snowden 2001; Mc-Cammon et al. 2002; Kavanagh et al. 2019). This is not an issue for us as we require an empirical model for the background. We use the powerlaw component with a fixed slope of 1.46 (Chen et al. 1997; Snowden et al. 2004; Kuntz & Snowden 2010) to model the cosmic X-ray background from unresolved point sources including active galactic nuclei (AGNs). We fit the sky model using the absorbed thermal models and powerlaw, together with the detector background model (described above). In the fitting, we allow the detector background const parameter to vary, but otherwise, we fix the shape of the detector background; the fit is performed over 0.30 keV to 11.0 keV. Once a good fit is obtained, we freeze the sky model parameters, and allow a multiplicative const factor (initially frozen at 1.0) to vary.

When fitting a source spectrum, we freeze the parameters that affect the detector and sky background model shapes while allowing the overall normalizations to vary through multiplicative constants for the detector and sky backgrounds (see, for example, Maggi et al. 2016; Garofali et al. 2017). Table 3 presents the background model and Figure 2 shows the background fit. As we show later in Sections 4.1 and 4.2.1, the background is significantly lower than the source spectra in the interior as well as on the rim, respectively, for most of the band-pass except at the highest energies (E > 5.5keV).

3.2. Source Models

For all of the (source) regions we analyze in this work, we take a two component absorption model to account for Galactic (tbabs) and LMC (tbvarabs) absorption by gas, molecules and grains along the line of sight. Following Dickey & Lockman (1990), we fix the Galactic Hydrogen column density $N_{H,Gal}$ to $5.5 \times 10^{20} \text{ cm}^{-2}$ with solar abundances (Wilms et al. 2000) whereas we allow the LMC hydrogen column density to vary. For all spectral fits, we set the initial guess for LMC elemental abundances to be $0.4 \times$ solar on the Wilms et al. (2000) scale, in line with the estimated metallicity of the LMC (Dufour et al. 1982; Russell & Dopita 1992; Westerlund 1997). Due to the limited number of counts in the energy range 0.3 - 0.5 keV in our spectra, where emission from C and N is prominent, we tie the C and N abundances to O in the source models. Similarly, due to poor constraints on the abundances of S, Ar, and Ca and the possibility of the L-shell emission of these elements affect-

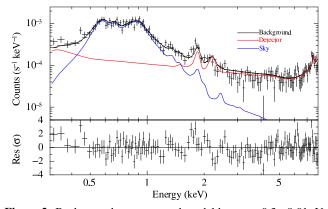


Figure 2. Background spectrum and model between 0.3-8.0 keV. Background model (black) is a mixture of detector (red) and sky (blue) components. The detector component consists of a broken power law (bkn2pow) and multiple Gaussians whereas the sky component consists of two thermal (apec) models and a powerlaw model. The thermal models dominate from 0.5 -1.0 keV and the detector background dominates above 2.0 keV. The background becomes significant above 5.5 keV.

ing fits at lower energies, we tie them together. We cannot constrain the abundance of Ni with the current data due to low number statistics, and tie it to that of Fe. For all the fits, we utilize the energy range between 0.3-7.0 keV, except for the regions where we study Fe K emission and extend the fit to 7.5 keV (see Section 3.2.3 for details).

With the angular resolution of Chandra, we can separate the forward shock from the rest of the remnant along the rim. We fit the rim regions with a plane-parallel shock model (vpshock; see Borkowski et al. 2001), because we expect to find a shock running into relatively cold and mostly neutral material. This model loses its accuracy when the conditions in the emitting region depart significantly from its assumptions, for example, the temperature and/or density vary across the region, or the material is already heated by previous shocks or thermal conduction (Hamilton et al. 1983; Jones & Ellison 1991). Consequently, we add a non-equilibrium ionization (NEI) component (vnei) to the model to explain emission from plasma heated to some temperature and evolved for a particular time (τ) , while not including emission from earlier times (see, for example, Masai 1994; Borkowski et al. 2001; Ellison et al. 2007). It also allows for the possibility of the detection of ejecta fragments if we allow the abundances of the vnei component to vary. In cases where the source model consists of more than one component, we start the fit by fixing the abundances of one or more vnei components to be the same as that of vpshock component.

Apart from the vpshock and vnei models, we also investigate the case of a recombining plasma which may be responsible for emission in the Fe K complex. In the case of a recombining plasma, the ionization temperature of ions

Table 3. Best-fit parameters of the background model, consisting of the detector and the sky components. Errors represent the 68 per cent confidence intervals which correspond to 1σ in the Gaussian case. Parameters without errors were frozen in the fit.

Component	Parameter	Units	Value
Detector	bkn2pow PhoIndex1		$1.60^{+1.17}_{-0.58}$
	bkn2pow BreakE1	keV	$0.50_{-0.03}^{+0.03}$
	bkn2pow PhoIndex2		$0.46^{+0.03}_{-0.03}$
	bkn2pow BreakE2	keV	$4.58^{+0.70}_{-0.49}$
	bkn2pow PhoIndex3		$1.51_{-0.54}^{+0.70}$
	bkn2pow Norm	photons keV $^{-1}$ cm $^{-2}$ s $^{-1}$	$1.433^{+0.001}_{-0.001} imes 10^{-3}$
	gaussian l Line E	keV	$11.314_{-0.188}^{+0.226}$
	gaussian l Sigma	keV	$1.954_{-1.23}^{+0.145}$
	gaussian l Norm	$\rm photons cm^{-2} s^{-1}$	$6.893^{+0.008}_{-0.007}\times10^{-2}$
	gaussian2 LineE	keV	1.487
	gaussian2 Sigma	keV	0.0
	gaussian2 Norm	$\rm photons cm^{-2} s^{-1}$	$3.868^{+3.680}_{-3.476}\times10^{-5}$
	gaussian 3 Line E	keV	$1.860^{+0.007}_{-0.012}$
	gaussian 3 Sigma	keV	0.0
	gaussian 3 Norm	$\rm photons cm^{-2} s^{-1}$	$4.650^{+0.573}_{0.055}\times10^{-4}$
	gaussian4 LineE	keV	$2.212^{+0.012}_{-0.123}$
	gaussian 4 Sigma	keV	$0.060^{+0.028}_{-0.019}$
	gaussian4 Norm	$\rm photons cm^{-2} s^{-1}$	$5.070^{+0.808}_{-0.698}\times10^{-4}$
	gaussian 5 LineE	keV	$7.555^{+0.019}_{-0.008}$
	gaussian 5 Sigma	keV	0.0
	gaussian 5 Norm	$\rm photons cm^{-2} s^{-1}$	$3.648^{+0.580}_{-0.555} imes 10^{-4}$
	gaussian 6 Line E	keV	$9.853_{-0.017}^{+0.030}$
	gaussian 6 Sigma	keV	$0.050^{+0.030}_{-0.050}$
	gaussian 6 Norm	$\rm photons cm^{-2} s^{-1}$	$8.780^{+1.649}_{-1.552}\times10^{-4}$
Sky	TBabs N_H	cm^{-2}	$0.186^{+0.132}_{-0.052}\times10^{21}$
	apec $1 kT_e$	keV	$0.175^{+0.009}_{-0.023}$
	apec1 Norm	cm ⁻⁵	$1.578^{+3.001}_{-0.427}\times10^{-4}$
	apec $2 kT_e$	keV	$0.768^{+0.040}_{-0.051}$
	apec2 Norm	cm ⁻⁵	$3.097^{+1.002}_{-0.431}\times10{-5}$
	powerlaw PhoIndex		1.46
	powerlaw Norm	photons keV $^{-1}$ cm $^{-2}$ s $^{-1}$	$3.404^{+1.049}_{-1.346} \times 10^{-6}$

exceeds the electron temperature (McKee 1974; Itoh 1977). We use the non-equilibrium plasma model vrnei which is a modified version of vnei in which the initial temperature (kT_init) can be specified; the model starts in collisional ionization equilibrium at kT_init, the temperature is changed to kT, the ionization state evolves at constant kT and density. A vrnei with kT_init set to 0.0808 keV is equivalent to vnei. If kT_init exceeds kT, the model evolves by recombining. As with vnei, the emission is calculated at a specific value of τ . We describe this further in Section 3.2.3. In the following subsections, we lay out the fitting algorithms for the different regions we analyze.

3.2.1. Rim Regions

We define rectangular regions on the rim wherever possible; some regions are distorted in shape to account for the locally non-uniform curvature of the remnant. All the regions around the rim (r1-r19, b1-b2) have nearly the same width (0.6-0.7 pc) and have at least 3500 counts in the 0.3-7.0 keV bandpass. We follow the following procedure to fit the rim regions and the blobs:

- 1 Fit the spectrum of a region on the rim with a source model (tbabs \times tbvarabs \times vpshock), with abundances fixed at 0.4 \times solar (Borkowski et al. 2007).
- 2 If the fit is acceptable in step 1 (following the criteria we describe in Section 3.3), note the abundances.
- 3 If the fit is not acceptable, allow the abundances of O, Ne, Mg, Si, S, and Fe to vary one by one. If it is acceptable after the abundances have been allowed to vary, note the best-fit abundances and error bars.
- 4 Fit all the regions on the rim in the same manner. After this step, all regions would have been fitted once with vpshock.
- 5 Find an average abundance for each element from regions where the fit in steps 1 or 3 was acceptable.
- 6 Refit the regions where the fit was not acceptable in steps 1 or 3 with the mean abundances calculated in step 5.
- 7 If the fit is still not acceptable in step 6, add an NEI component (vnei) to the source model and refit.

As we show in Section 4.1, for the two regions on the rim where a single vpshock did not generate an acceptable fit, the two-component model satisfactorily fits the spectra. Thus, we do not go beyond step 7 to fit any region on the rim. Finally, to calculate the mean local LMC abundances for all elements, we add an additional step in the algorithm in which we fit all of the rim spectra with the abundances of O, Ne, Mg, Si, S, and Fe free. This is necessary to get meaningful uncertainties on the average abundances which would otherwise be underestimated if some elemental abundances were held fixed in some regions (Maggi et al. 2019).

3.2.2. Region e1

We examine the O-rich ring seen in the optical in N132D (Morse et al. 1995; Blair et al. 2000), also called the *Lasker's Bowl*, as an interior region that might exhibit enriched abundances in the X-ray spectral data. The presence of ejectarich knots in X-rays in this ring was previously reported by Borkowski et al. (2007, see their Figure 2). We select region e1 on this ring which overlaps with both the ejectarich knots marked in the X-ray data and the O-rich ejecta seen in the optical. The spatial coincidence of optical O-rich ejecta

and X-ray enhancements in O, Ne, Mg, Si, and Fe emission point to e1 being a complex region in which multiple components with different plasma conditions are contributing. Moreover, its location also overlaps with a region which shows O and Ne rich ejecta in the $14-36 \mu m$ infrared map of N132D (Tappe et al. 2012, see their region I in Figure 1). To fit this region, we use an NEI component (vnei), and add a vpshock component to account for the shell emission.

3.2.3. Regions with Fe K Emission

N132D is one of the few extragalactic SNRs for which direct measurements of the spatial distribution of Fe-rich ejecta can be made. The Fe K α complex ranges from 6.4 keV for neutral Fe to 7.0 keV for Fe XXVI. The spectrum of the entire remnant indicates a peak in emission at $\sim 6.7 \,\text{keV}$ (presumably Fe XXV emission). A center-filled excess of Fe K emission was detected in the observations of N132D taken by XMM-Newton (Behar et al. 2001), however, Chandra data reveals that the extent of this emission is spread largely across the southern part of the remnant. As we show in Figure 3, we create three 0.4 keV wide passbands to sample this Fe K emission and the surrounding continuum: 6.1-6.5, 6.5-6.9and 6.9-7.3 keV (see also, Figure A.2). We then select six large regions (f1-f6) to study the Fe K emission feature in this remnant. We select enough regions such that they collectively sample the majority of the Fe K counts observed in the spectrum, and exclude areas where the pileup fraction is high, as shown in Figure A.1. The analysis of a single spectrum from the entire southern half of the remnant combines data from regions with different plasma conditions such that a complex, multi-component model is necessary to represent the data. Thus, it is more meaningful to analyze the spectra on smaller spatial scales in which the inherent variations in the plasma conditions are smaller.

For regions where we study emission from Fe K lines, we fit the spectra in the energy range 0.3-7.5 keV to sufficiently sample the continuum on either side of the feature at 6.7 keV. We present analyses based on both ionizing and recombining plasma models for regions f1 - f6. SNRs interacting with molecular clouds are frequently associated with recombining plasma, although the mechanism which produces the recombining plasma is not clear. One possibility is thermal conduction between the remnant shell and the cloud as suggested by Rho & Petre (1998). A commonly quoted evidence for this scenario is the anti-correlation between electron temperature and recombining timescale (e.g., Katsuragawa et al. 2018; Okon et al. 2018, 2020). On the other hand, an overionization of the plasma is possible if the shock evaporates the cloud (White & Long 1991). Itoh & Masai (1989) and Yamaguchi et al. (2009) suggest that an overionized plasma may be produced by rapid adiabatic expansion if the shock propagates from a region of high density to a region of low

density (Shimizu et al. 2012). In this scenario, a positive correlation is observed between the electron temperature and recombining timescale (e.g., Yamaguchi et al. 2018). Detailed simulations of the X-ray emission from an SNR shock interacting with a distribution of clouds in the ISM conducted by Zhang et al. (2019) show that both thermal conduction and adiabatic expansion are likely to produce radiative recombination emission at different locations in the remnant (see also, Zhou et al. 2011).

Non-equilibrium ionization in SNRs typically manifests itself as 1. an ionizing plasma, or 2. a recombining plasma. In the former case, the plasma is underionized; the ionization stages and line ratios reflect ionization temperature $kT_z < kT_e$. The plasma evolves via ionization, and the radiative recombination continuum (RRC) features are weak. In the latter case, the plasma is overionized, the ionization stages and line ratios reflect $kT_z > kT_e$. The plasma evolves via recombination, and has strong RRC features, with the continuum featuring sawtooth-like excesses extending upward in energy from the ionization potential, and line ratios exceeding the expectations for collisional ionization equilibrium due to radiative cascade populating higher levels.

The basic ionizing plasma vs. recombining plasma features for SNR spectra have been long understood (Itoh 1977; Mewe & Gronenschild 1981; Gaetz 1990; Masai 1994). The shocking of low temperature material results in ionization to more excited states. Eventually adiabatic cooling dominates as the remnant expands. Ultimately the plasma becomes overionized, with a recombining plasma. The surprising aspect of recent discoveries of recombining plasmas was that the plasmas are strongly recombining, with kT_z greatly exceeding $kT_{\rm e}$ with significant radiative RRCs, and significant line ratio and ionization state anomalies. Kawasaki et al. (2002) proposed an overionized plasma based on anomalous line ratios in Advanced Satellite for Cosmology and Astrophysics (ASCA) observations of SNR IC 443. The existence of strongly recombining plasmas in SNRs was established by Yamaguchi et al. (2009) with the discovery of radiative recombination continua (RRCs) of H-like Si and S in Suzaku observations of SNR IC 443, and that of H-like Fe in Suzaku observations of SNR N49B by Ozawa et al. (2009).

The strength of the RRC emission depends on the electron temperature, the ion temperature and the ionization timescale (see Yamaguchi et al. (2009) for a discussion). The presence of hot, He-like Fe plasmas in N132D is suggestive of recombining plasma. The Fe K RRC feature in the *Chandra* spectra is difficult to disentangle from systematic instrument characteristics like decreasing effective area and increasing detector background at $\gtrsim 7 \text{ keV}$, and the ability to detect excess K β over K α is also limited by the CCD spectral resolution and the low sensitivity achieved in the $\sim 90 \text{ ks}$ of available data. In principle, Hitomi Collaboration et al. (2018) obser-

vations of N132D with low background could potentially be used to constrain the H-like K α to He-like K α ratio that can provide evidence for a recombining plasma (Kawasaki et al. 2002; Porquet et al. 2010; Lopez et al. 2013), however, the low number of counts in the *Hitomi* spectrum makes such an analysis challenging, and is beyond the scope of this paper. As we show later in Section 4.2.2, it is thus not possible to provide a definitive case for the existence of a hot Fe K emitting recombining plasma in the remnant. Nevertheless, we examine this case as a possible alternative to the ionizing case.

For the case of an ionizing plasma, we introduce a two component vnei, where the cooler component explains the soft X-ray spectrum and Fe L emission, and the hotter component explains the hard X-ray spectrum and Fe K emission. For the case of a recombining plasma, we use the recombining collisional plasma model vrnei, together with a vnei which can account for the low temperature plasma. Both models also contain a vpshock component to represent the shell emission along the line of sight. As we show in Section 4.2.2, such three-component models (vnei/vrnei + vnei + vpshock) are necessary to account for the Fe K emission in these regions.

3.3. Fit Evaluation

We use the C-statistic (which approximates the Poisson log-likelihood) to evaluate the spectral fits since it does not introduce a bias in the case of a low (or null) number of counts per spectral bin (Cash 1979; Nousek & Shue 1989; Leccardi & Molendi 2007). We further use the goodness-offit criterion developed for the C-statistic by Kaastra (2017), by comparing the observed value of the C-statistic (cstat (O)) with the expected value (cstat(E)) and expected variance determined from the predicted model counts in each bin, using the numerical estimates derived by Kaastra (2017). We show both the expected value and the width of the distributions that would result when the fit is good. We adopt the following criterion to determine if a fit is acceptable if $cstat(E) - 2.6\sigma_E < cstat(O) < cstat(E) + 2.6\sigma_E$, where σ_E^2 is the expected variance of cstat(E) and we choose the bounds such that the probability that cstat(O) falls outside the range is 1 per cent.

4. RESULTS

4.1. Rim Regions and Blobs

Using the fit evaluation criteria we outline in Section 3.3, we find that spectral analysis of 17 out of the 19 rim regions produce an acceptable fit with the single component vpshock model, which we summarize in Table 4. For the two regions where the single model fit fails, we re-do the fitting while adding a vnei component. We present the results for the two-component model in Table 5.

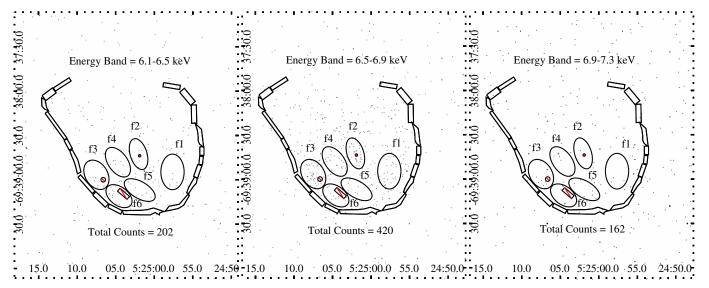


Figure 3. Spatial distribution of counts in the energy range 6.1-7.3 keV in N132D. From left to right, images are shown for energy ranges 6.1-6.5, 6.5-6.9 and 6.9-7.3 keV, respectively. Rim regions mark the extent of the remnant. The middle panel shows emission from Helike Fe K α (~ 6.7 keV), while the adjacent lower and higher energy bands indicate the continuum levels. The middle energy band shows a significant excess compared to the continuum.

Table 6 shows the mean abundance values (μ , with $1\sigma_{\mu}$ errors) we calculate for the rim and the scatter in each parameter. We emphasize that the mean values we calculate are from fitting the abundances of O, Ne, Mg, Si, S, and Fe in all the rim regions; this prevents bias in the estimate of the mean due to some fits having some parameters frozen. We follow the method of Multiple Imputations (Lee et al. 2011) to find the error on the mean (σ_{μ}) and the scatter, which takes into account the statistical as well as systematic uncertainties (in other words, within and between variance). We present the details of this method in Appendix B. If the scatter in an elemental abundance along the rim is < 1 (implying that there is more systematic than statistical error), we consider its variation to be insignificant. If the best-fit abundance and associated 1σ error in any region on the rim is more than $\mu + \sigma_{\mu}$ or less than $\mu - \sigma_{\mu}$, we classify it as being enhanced or reduced, respectively.

A single component vpshock model provides an adequate fit (evaluated using the criteria described in Section 3.3) for regions r1, r2, r4–r9, r11–r19, b1, and b2. Figure 4 shows the spectral fit with this model for region r1, along with the background to emphasize that the background counts are significantly less than the source counts (see Appendix C for all other spectral fits of the rim regions and the blobs). However, some peculiarities are noticeable in the fits: regions r1 and r2 show systematic residual deviations around 1.5-2 keV and 0.5-0.6 keV respectively; r6 and r7 show excess Fe; r11 underpredicts the flux near 1.2 keV; r13–r15 require a lower abundance of Mg; r14 is also underabundant in O, Ne, and Si; r16 shows higher than mean levels of S, and r17 shows enhanced S; b1 is consistent with excess Fe; and b2 appears to contain ambient ISM material. Regions r3 and r10 are poorly fit with this model, and we re-fit them with the more complex <code>vpshock+vnei</code> model. We find that these regions show an additional plasma component with a higher temperature than the shell emission, which has been recently excited given their low ionization timescales. Unlike the single-component fits, the difference between <code>cstat</code> (O) and <code>cstat(E)</code> is well within the $2.6\sigma_E$ limit.

Figure 5 depicts the trends seen along the rim in the parameters of interest, for the single vpshock model. We see the column density along the line of sight (N_H) to be higher in the southern part of the remnant than in the western and eastern parts which corresponds to presumably denser material (molecular clouds) present in that direction, as has been observed in the NANTEN CO survey (Fukui et al. 2008), the Magellanic Mopra Assessment (MAGMA) survey of CO in the LMC with the Mopra telescope (Wong et al. 2011), and high resolution ALMA observations of N132D (Sano 2019). In fact, many southern rim regions spatially coincide with the locations of shocked ISM clouds found by Dopita et al. (2018, see their Figure 2) in the optical. The ionization timescale (τ) is roughly uniform over the shell and its values are indicative of a non-equilibrium plasma.

Figure 6 shows the abundance pattern across the rim for O, Ne, Mg, Si, S and Fe. Note that the fit results plotted in Figure 6 are not the same as in Table 4 as we explain above. The shaded areas correspond to $1\sigma_{\mu}$ deviations from the mean abundance value, where σ_{μ} accounts for the statistical as well as systematic uncertainty around the mean. The thick dashed lines mark the mean value. In summary:

1. O: The abundance of O is uniform along the rim, except in region r2, where it is enhanced.

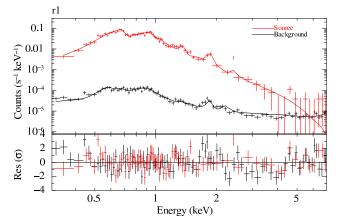


Figure 4. Spectral fit for region r1 on the rim with the single vpshock model. Also plotted is the background model fit that shows that the background is significantly less than the source spectrum below 5.5 keV. Note that the data have been rebinned for plotting purposes. All other spectral fits for the rim regions and the blobs are present in Appendix C.

- 2. Ne: The abundance of Ne is within σ_{μ} of the mean throughout the rim.
- 3. Mg: The scatter in the abundance of Mg is < 1, implying that the variance between the different measurements is less than that within the measurements.
- 4. Si: The abundance of Si is also uniform across the rim, however, the scatter is more than one, implying the presence of localized variations. Further, region r8 is marginally consistent with the average.
- 5. S: We are cautious while thawing the abundance of S in the fits, because of the caveats listed in Section 3. Although it is poorly constrained on the rim regions due to low counts, region r17 shows a significant enhancement. The scatter in S > 1, again implying the presence of localized variations.
- 6. Fe: The abundance of Fe is uniform over the rim. Like Mg, the scatter in the abundance of Fe < 1.

Based on our spectral analysis and the evaluation criteria for enhanced/reduced abundance measurements, we find that the abundances are largely uniform around the rim. The two exceptions to this are the enhanced O on the north-western rim (region r2) and S on the north-eastern rim (region r17).

4.2. Interior Regions

In this section, we describe results from the spectral analysis of the interior regions e1 and f1-f6 that were selected from narrow-band and hardness ratio images as having enhanced abundances and signatures of Fe K emission, respectively.

4.2.1. Region with Enriched Abundances

Table 5 shows the fit results for region e1 and Figure 7 shows the source spectra with the best-fit model. The results reveal enriched abundances ($\gtrsim 2.5 \times$ mean) of all elements (except S) in this region, consistent with the excess flux at different line energies we observe in the narrow band images. Adding a single NEI component to the model fits the observed spectrum well with an electron temperature of $\sim 2.0 \, \text{keV}$. The higher temperature of the vnei as compared to the shell emission from the rim implies the presence of one or multiple shock heated ejecta clumps in this region. The shorter ionization timescale indicates that the ejecta-rich clump(s) present in this region have been recently heated by the shock. The best-fit abundances have large uncertainties due to low number of counts. Nevertheless, they are significantly higher than the LMC abundances. We use the best-fitting parameters from the fit for this region to deduce the mass of the progenitor in Section 5.3. The coeval presence of optical and X-ray emitting ejecta in a region has also been observed in SNR G292.0+1.8 and Cas A, where the optical emission is proposed to come from dense ejecta-rich knots and the X-ray emission from a lower density plasma (Ghavamian et al. 2005; Patnaude & Fesen 2014).

4.2.2. Regions with Fe K Emission

We use a vnei + vnei + vpshock model (referred to as the *ionizing* model) to fit the spectra in regions f1-f6. We also use a recombining plasma model (vrnei + vnei + vpshock) as an alternate explanation to look for possible signatures of a recombining plasma in N132D. These models contain three components: one to account for shell emission along the line of sight (vpshock), second to account for the cooler soft X-ray emission and some of the high energy continuum (vnei2 and vnei in ionizing and recombining models, respectively), and third to account for the hotter Fe K emission and the remainder of the hard X-ray spectra (vnei1 and vrnei in ionizing and recombining models, respectively). We find that a three component fit is essential because no combination of a two component model of an NEI plasma is able to model the Fe K feature while simultaneously explaining the Fe L shell emission around 1 keV. Evidence for the need of a third, hotter component is established when we artificially increase the abundance of Fe in the NEI component of a two-component (vnei/vrnei + vpshock) model to reproduce the observed flux in the Fe K feature. This experiment of increasing the Fe abundance in order to get enough flux in the Fe K α line overproduces the Fe L emission at \sim 1 keV. Thus, we establish that at least two separate plasma conditions are needed to explain the Fe L (\sim 1 keV) and Fe K (\sim 6.7 keV) emissions, which has also been noted before for this remnant (Maggi et al. 2016; Bamba et al. 2018).

Table 4. Fit results of plane-parallel shock model (vpshock) on rim regions and blobs (see Figure 1 for the location of each region). The abundances are with respect to the Wilms scale (Wilms et al. 2000). Errors are the 68 per cent confidence intervals, equivalent to Gaussian 1σ around the quoted abundance.

Region ID	N _H	kT _e	τ	norm	0	Ne	Mg	Si	S	Fe	cstat(0)/dof	cstat(E) $\pm \sigma_{\rm E}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	$10^{22}{\rm cm}^{-2}$	keV	$10^{11} \mathrm{cm}^{-3} \mathrm{s}$	$10^{-4} {\rm cm}^{-5}$								
r1	$0.05^{+0.02}_{-0.02}$	$1.22_{-0.08}^{+0.11}$	$0.60^{+0.10}_{-0.09}$	$0.66^{+0.03}_{-0.04}$	0.46	0.59	0.44	$0.84_{-0.15}^{+0.17}$	0.40	0.29	816/911	778 ± 41
r2	$0.06^{+0.01}_{-0.01}$	$0.92^{+0.07}_{-0.04}$	$1.78^{+0.45}_{-0.38}$	$2.17^{+0.19}_{-0.29}$	$0.78^{+0.18}_{-0.13}$	0.59	$0.64_{-0.09}^{+0.11}$	$0.70_{-0.11}^{+0.10}$	0.40	$0.45_{-0.08}^{+0.10}$	869 / 908	802 ± 42
r3*	$0.08^{+0.01}_{-0.01}$	$0.75^{+0.03}_{-0.03}$	$2.12^{+0.25}_{-0.23}$	$6.03^{+0.39}_{-0.38}$	0.46	$0.46^{+0.03}_{-0.04}$	0.44	0.52	$0.81^{+0.20}_{-0.09}$	$0.32^{+0.03}_{-0.02}$	939 / 909	803 ± 42
r4	$0.09^{+0.02}_{-0.02}$	$0.82^{+0.03}_{-0.03}$	$1.79_{-0.20}^{+0.21}$	$2.57_{-0.11}^{+0.13}$	0.46	$0.54_{-0.05}^{+0.05}$	$0.49^{+0.06}_{-0.06}$	0.52	$0.82^{+0.28}_{-0.24}$	0.29	826 / 909	782 ± 42
r5	$0.09^{+0.02}_{-0.02}$	$0.71_{-0.02}^{+0.02}$	$3.29_{-0.33}^{+0.38}$	$2.35_{-0.10}^{+0.08}$	0.46	0.59	0.44	0.52	$0.75_{-0.25}^{+0.30}$	0.29	823 / 911	750 ± 41
r6	$0.15^{+0.03}_{-0.02}$	$0.82^{+0.11}_{-0.05}$	$1.82_{-0.64}^{+0.48}$	$1.45^{+0.19}_{-0.29}$	0.46	0.59	$0.59_{-0.08}^{+0.12}$	0.52	0.40	$0.37^{+0.10}_{-0.05}$	744 / 910	747 ± 40
r7	$0.06^{+0.01}_{-0.01}$	$0.80^{+0.04}_{-0.04}$	$2.70_{-0.40}^{+0.42}$	$3.16^{+0.22}_{-0.26}$	0.46	$0.48^{+0.04}_{-0.07}$	0.44	$0.70_{-0.05}^{+0.10}$	0.40	$0.39^{+0.05}_{-0.04}$	792 / 909	783 ± 41
r8	$0.15^{+0.02}_{-0.02}$	$0.82^{+0.09}_{-0.05}$	$1.60^{+0.30}_{-0.37}$	$2.71_{-0.39}^{+0.30}$	0.46	0.59	0.44	0.52	$0.66^{+0.24}_{-0.20}$	$0.34_{-0.04}^{+0.06}$	883 / 910	778 ± 42
r9	$0.18^{+0.03}_{-0.02}$	$0.70^{+0.03}_{-0.04}$	$1.67^{+0.33}_{-0.26}$	$1.63^{+0.12}_{-0.85}$	0.46	0.59	0.44	$0.71_{-0.14}^{+0.15}$	0.40	0.29	760 / 911	741 ± 41
r10*	$0.27^{+0.02}_{-0.03}$	$0.93^{+0.02}_{-0.01}$	$2.61_{-0.40}^{+0.27}$	$7.20^{+0.22}_{-0.25}$	0.46	$0.51_{-0.03}^{+0.03}$	0.44	0.52	0.40	0.29	967 / 911	855 ± 42
r11	$0.10^{+0.02}_{-0.02}$	$1.04^{+0.12}_{-0.07}$	$1.61_{-0.27}^{+0.46}$	$1.61^{+0.22}_{-0.13}$	$0.56^{+0.09}_{-0.08}$	0.59	$0.51^{+0.08}_{-0.07}$	0.52	0.40	$0.40^{+0.04}_{-0.06}$	872 / 909	779 ± 41
r12	$0.12^{+0.02}_{-0.02}$	$0.97^{+0.04}_{-0.03}$	$1.88^{+0.26}_{-0.23}$	$1.82^{+0.07}_{-0.08}$	0.46	0.59	0.44	$0.63^{+0.10}_{-0.10}$	0.40	0.29	822/911	797 ± 42
r13	$0.11^{+0.02}_{-0.02}$	$1.02^{+0.07}_{-0.07}$	$0.99^{+0.36}_{-0.20}$	$1.25^{+0.09}_{-0.08}$	0.46	0.59	$0.38^{+0.06}_{-0.06}$	0.52	0.40	0.29	849 / 911	784 ± 40
r14	$0.05^{+0.01}_{-0.01}$	$0.77^{+0.04}_{-0.03}$	$1.42_{-0.25}^{+0.31}$	$4.05_{-0.14}^{+0.15}$	$0.29^{+0.04}_{-0.03}$	$0.43^{+0.03}_{-0.03}$	$0.37^{+0.04}_{-0.04}$	$0.36_{-0.07}^{+0.07}$	0.40	0.29	827 / 908	789 ± 41
r15	$0.10^{+0.02}_{-0.02}$	$0.95^{+0.10}_{-0.08}$	$1.03_{-0.23}^{+0.31}$	$1.00^{+0.15}_{-0.14}$	0.46	0.59	$0.38^{+0.08}_{-0.08}$	$0.33_{-0.11}^{+0.12}$	0.40	$0.44_{-0.07}^{+0.08}$	789 / 909	758 ± 40
r16	$0.02^{+0.02}_{-0.01}$	$0.79^{+0.04}_{-0.03}$	$1.47_{-0.23}^{+0.16}$	$3.11_{-0.27}^{+0.32}$	0.46	$0.69^{+0.04}_{-0.03}$	0.44	0.52	$0.86^{+0.26}_{-0.23}$	0.29	827 / 910	786 ± 41
r17	$0.07^{+0.02}_{-0.02}$	$1.04^{+0.08}_{-0.07}$	$0.96^{+0.20}_{-0.18}$	$0.81^{+0.07}_{-0.06}$	0.46	$0.73^{+0.07}_{-0.06}$	0.44	0.52	$1.84^{+0.56}_{-0.47}$	0.29	767 / 910	766 ± 41
r18	$0.02^{+0.01}_{-0.01}$	$0.76^{+0.03}_{-0.02}$	$2.26^{+0.24}_{-0.22}$	$5.84^{+0.34}_{-0.35}$	0.46	$0.45^{+0.03}_{-0.03}$	0.44	0.52	0.40	$0.36^{+0.03}_{-0.02}$	883 / 910	804 ± 42
r19	$0.02^{+0.01}_{-0.01}$	$0.71^{+0.02}_{-0.01}$	$5.48^{+0.64}_{-0.58}$	2.46 ^{+0.07} _{-0.08}	0.46	$0.69^{+0.06}_{-0.06}$	0.44	0.52	0.40	0.29	800 / 911	758 ± 41
b1	$0.10^{+0.03}_{-0.02}$	$0.86^{+0.09}_{-0.08}$	1.59 ^{+0.86} _{-0.50}	$0.63^{+0.13}_{-0.10}$	$0.83^{+0.45}_{-0.24}$	0.59	0.48	0.58	0.73	$0.53^{+0.15}_{-0.12}$	770 / 910	730 ± 39
b2	$0.22^{+0.03}_{-0.03}$	$1.12_{-0.10}^{+0.08}$	$0.95^{+0.30}_{-0.15}$	$0.88^{+0.07}_{-0.05}$	0.46	0.59	0.44	0.52	0.40	0.29	848 / 912	797 ± 40

NOTE—Columns 2-5 describe the LMC hydrogen column density, electron temperature, ionization timescale and normalization parameter, respectively. Columns 6-11 describe the best-fit abundances of each element. Column 12 lists cstat(O) which is the observed C-statistic we obtain from Xspec; cstat(E) listed in column 13 is the expected C-statistic from the Kaastra (2017) formulation. The fits are considered unsuccessful if $|cstat(O) - cstat(E)| > 2.6\sigma_E$ where σ_E^2 is the expected variance of cstat(E). Regions with asterisk (r3 and r10) are those which could not be fit with a single vpshock model; they were re-fit with a more complex model as described in Table 5. In region r11, the best-fit shows an enhanced abundance of N (which is otherwise tied to O): N = 0.80 \pm 0.11. The mean values derived from fitting all the abundances in all the regions are present in Table 6. Spectral fits for all regions are present in Appendix C.

We show the best-fit parameters for the ionizing and recombining models for regions $f_{1}-f_{6}$ in Table 7, and the corresponding spectral plots in Figures 8, C.11, C.12, C.13, C.14, and C.15, respectively. Note that the total emission (top black histogram and curve) includes the background model, which is why it levels off at a higher level than the magenta curves in the inset in these Figures. There are several features of these fits that should be highlighted. Firstly, the quality of the fit in terms of the fit statistic cstat (0) /dof is indistinguishable for the *ionizing* and *recombining* plasma models in all the regions. Based on these results we can not conclude that one model is preferred over the other. We also note that the initial electron temperature (kT init) for the vrnei component in the recombining models is highly degenerate and gives similar results for temperatures higher than 10keV (see also, Bamba et al. 2018); hence, we freeze it at this value (see, for example, Auchettl et al. 2017; Katsuragawa et al. 2018). Further, we find that both the model fits for regions f1, f2, f4 and f6 are acceptable according to our criteria whereas those for region f3 and f5 are marginally inconsistent with our chosen acceptability criteria because for the latter two, $cstat(0) \approx cstat(E)+3.1 \sigma_E$. This indicates that overall the fits are good, however, there are details which the models fail to reproduce. It also highlights the tradeoff between using large regions that encompass sufficient Fe K emission and the existence of multiple plasma conditions within them that complicate the spectral modeling.

The electron temperatures and ionization timescales for the shell and the cooler X-ray emission model components are identical in both the models in all the six regions; they fall in the partial non-equilibration category as defined by Vink (2012, see their Section 5.3). Additionally, both the best-fit ionizing and recombining plasma models result in abundances for Si and Fe (in the hotter component) that are sig-

Region ID	N_H	kT_e	τ	norm	kT_e	τ	потт	0	Ne	Mg	Si	s	Fe	cstat (O)/dof cstat(E) $\pm \sigma_{\rm E}$	cstat (E) $\pm \sigma_{ m E}$
(1)	(2)	(3)	(4)	(5)	(9)	E	(8)	(6)	(10)	(11)	(12) (13) (14)	(13)	(14)	(15)	(16)
:	$10^{22}{ m cm}^{-2}$	keV	$10^{22} \mathrm{cm}^{-2}$ keV $10^{11} \mathrm{cm}^{-3} \mathrm{s}$ $10^{-4} \mathrm{cm}^{-5}$	$10^{-4}{ m cm}^{-5}$	keV	$10^{11} \mathrm{cm}^{-3}\mathrm{s}$ $10^{-4} \mathrm{cm}^{-5}$	$10^{-4}{\rm cm}^{-5}$:	:	:	:	:	:	:	:
r3	$0.10\substack{+0.02\\-0.02}$	$0.64_{-0.03}^{+0.02}$	$0.10^{+0.02}_{-0.02} 0.64^{+0.02}_{-0.03} 6.14^{+2.39}_{-1.48} 6.41^{+0.52}_{-0.74}$	$6.41_{-0.74}^{+0.52}$	$1.64_{-0.47}^{+0.59}$	$0.05^{+0.03}_{-0.02}$	$0.56_{-0.19}^{+0.32}$	0.46	0.59	$0.48^{+0.06}_{-0.06}$	$0.48^{+0.06}_{-0.06} 0.57^{+0.13}_{-0.12} 0.40$	0.40	0.29	888 / 907	829 ± 42
r10	$0.24\substack{+0.03\\-0.03}$	$0.24^{+0.03}_{-0.03}$ $0.76^{+0.08}_{-0.06}$	$3.21_{-0.61}^{+0.85}$	$5.78^{+1.36}_{-0.94}$	$1.54_{-0.33}^{+0.67}$	$0.69\substack{+0.30\\-0.21}$	$1.55_{-0.85}^{+0.90}$	0.46	0.59	0.44	0.52	0.40	0.29	943 / 909	878 ± 43
e1	$0.09^{+0.02}_{-0.01} 0.61^{+0.35}_{-0.09}$	$0.61_{-0.09}^{+0.35}$	$0.70_{-0.20}^{+0.20}$	$1.47_{-0.19}^{+0.32}$	$2.02^{+1.29}_{-0.68}$	$0.42_{-0.08}^{+0.38}$	$0.25_{-0.16}^{+0.07}$	$1.63_{-0.29}^{+0.64}$	$1.59^{+1.00}_{-0.42}$	$1.59^{+1.00}_{-0.42} 2.50^{+1.27}_{-0.35} 1.70^{+0.86}_{-0.21} 0.40 0.96^{+0.47}_{-0.37}$	$1.70^{+0.86}_{-0.21}$	0.40	$0.96_{-0.37}^{+0.47}$	858 / 904	803 ± 41

Table 5. As in Table 4, for fit results of vpshock+vnei model on rim regions (where the single vpshock did not yield an acceptable fit) and region e1. The spectral fits for the rim regions are present in Appendix C and for region e1 in Figure 7.

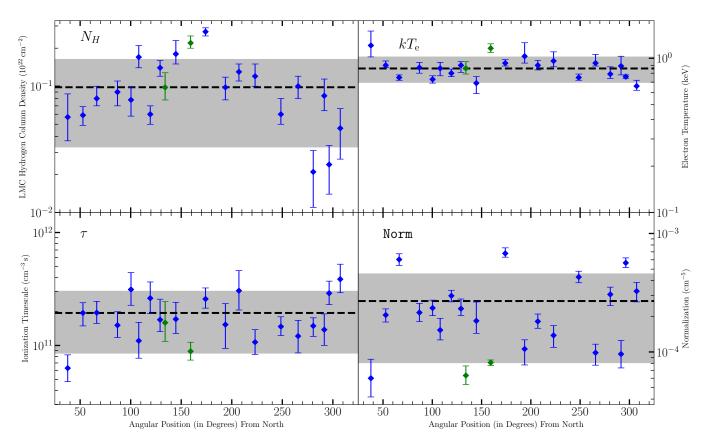


Figure 5. Trends along the rim for a plane-parallel shock model (vpshock). Horizontal axis depicts the angular position of each region (in degrees) clockwise from the North. Blue markers denote values for the rim regions, and green markers denote values for the blobs (see Figure 1 for information on the location of each region). Dashed line depicts the mean local LMC value for each parameter (see Table 6) and the shaded area corresponds to the total (statistical+systematic) uncertainty on the mean.

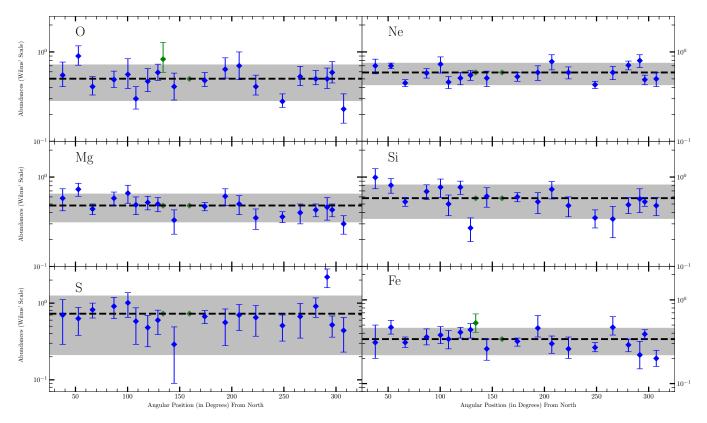


Figure 6. Same as Figure 5, showing abundance pattern across the rim. Vertical axis is the abundance value relative to cosmic, on Wilms et al. (2000) scale. Blue markers denote values for the rim regions, and green markers denote values for the blobs. The shaded area depicts the $\mu \pm \sigma_{\mu}$ domain for each abundance, where μ is the average value local to N132D (denoted by dashed lines) and σ_{μ} is the total (statistical+systematic) uncertainty on the mean that we use as a criteria to classify an abundance as enhanced/reduced (see Appendix B). The mean local LMC value (μ) for each parameter is available in Table 6, along with a comparison with other works in Table 8.

Table 6. Mean (μ) local LMC parameters, obtained from the fits to the rim regions. Error (σ_{μ}) denotes the statistical as well as systematic uncertainty on the mean. Abundances are quoted with respect to the Wilms scale. Uniformity of a parameter over the shell is judged by its scatter value. Both σ_{μ} and scatter are calculated from the method of Multiple Imputations (see Appendix B).

Parameter	Units	$\mu \pm \sigma_{\mu}$	Scatter
N _H	$10^{22}{\rm cm}^{-2}$	0.10 ± 0.07	2.74
kT _e	keV	0.86 ± 0.16	1.37
τ	$10^{11}{\rm cm}^{-3}{\rm s}$	1.94 ± 1.09	1.26
0		0.50 ± 0.22	1.00
Ne		0.59 ± 0.16	1.01
Mg		0.48 ± 0.17	0.93
Si		0.58 ± 0.24	1.14
s		0.73 ± 0.52	1.18
Fe		0.34 ± 0.12	0.96
norm	$10^{-4} \mathrm{cm}^{-5}$	2.69 ± 1.88	4.10

nificantly enhanced compared to the expected abundances for the LMC in 4 out of the 6 regions. The enhanced abundance

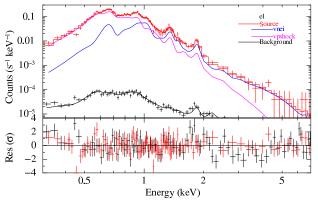


Figure 7. Fit and residuals for region e1 with the (vpshock + vnei) model. The best-fit parameters are listed in Table 5. This region shows enhanced abundances ($\gtrsim 2.5 \times$ mean) of all elements (except S) and contains one or more X-ray bright ejecta fragments. It partially overlaps with the ejecta fragment seen in the optical (Morse et al. 1996, 1995; Blair et al. 2000) as shown in Figure 1. Also plotted is the background that is significantly lesser than the source at energies < 5.5 keV. Note that the spectral counts have been rebinned for display purposes.

of Fe in these regions distinguishes them from the regions at the rim. The regions interior to the remnant contain plasma with a sufficiently high temperature and Fe abundance to produce the observed Fe K emission. We also let the abundances of O, Ne and Mg vary and find that both the best-fit models have enriched Ne and Mg in the cooler model component in regions f1 and f6, and in the recombining plasma model in region f3.

Although there are several similarities in the two models that lead us to conclude they cannot be distinguished with the current data, there are subtle differences that provide some understanding of the plasma conditions in these regions. For example, cstat (0) is slightly lesser for the recombining plasma models in regions f1, f2, f3 and f6; the ionization timescale for the hotter NEI component in the ionizing model (vneil) approaches equilibrium within the uncertainties in regions f3, f4 and f6 whereas that for the recombining model essentially represents non-equilibrium plasma (except perhaps for region f6). This could imply that the plasma is in fact evolving through recombination post equilibrium. The recombining models also exhibit typical LMC abundance of S in the vrnei component, except for region f4. The constraints on best-fit abundances are tighter in the recombining models, and there are no values that might be nonphysical and simply a result of the complex nature of the fit; for example, the abundance of Si in the hotter model component in region f2 in the ionizing model, which is $\sim 7 \times$ the solar value. The hottest plasma component in the recombining model contributes more to the emission at lower energies than the ionizing model, while both components explain the Fe K emission. A similar observation can also be made by realizing that the emission measures (norm) of the hotter component in the recombining model is larger than that in the corresponding ionizing model, except for region f6. This hints at the possibility of different origins of the hot plasma in different parts of the remnant, as has been shown for the SNR G290.1-0.8 (Kamitsukasa et al. 2015), as well as in simulations of an SNR shock interacting with a distribution of clouds in the ISM (Zhang et al. 2019), however, no definitive conclusions on the origin of the hot component can be drawn from the current data².

Thus, we establish from this analysis that: 1. Fe K emission in N132D is not contained in a single ejecta clump or discrete feature, rather, it is largely spread across the southern half of the remnant, and 2. the plasma that leads to the production of Fe K is either hot with a surprisingly large value of the ionization timescale or undergoing recombination (with slight indications in the favor of the latter). In either case this plasma is physically distinct from the plasma that produces

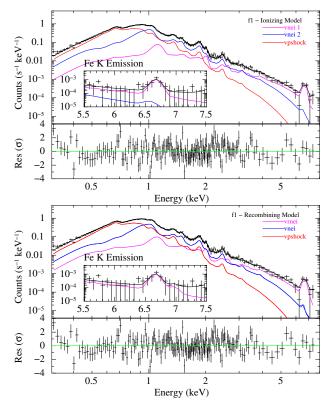


Figure 8. Fits and residuals for the region f1, showing the weak Fe K emission feature present at $\sim 6.7 \text{ keV}$. Inset zooms into the energy range 5.5-7.5 keV that contains this emission. The fit parameters for both the ionizing and recombining models are presented in Table 7. With the current number of counts, it is difficult to distinguish between the origin and the nature of the plasma since the spectral fits of both the models are statistically same. Note that the spectral counts have been rebinned differently in the main plot and the inset for display purposes. Spectral plots for other Fe K regions are present in Appendix C.

the soft X-ray emission. We further discuss its implications in Section 5.4.

5. DISCUSSION

5.1. LMC Abundances and Their Variations

Analysis of the rim regions provides a means to estimate the LMC abundances local to N132D that can inform us about the metallicity of the circumstellar medium (CSM) prior to the explosion. Table 8 shows the mean abundances for the elements we include in this study, along with measurements from previous works. Before we can meaningfully compare these abundances, it is important to remark on several characteristics that influence these measurements and should be kept in mind. The first row of Table 8 lists the number of regions used by different authors to determine the mean local abundances; 'W' denotes that certain studies derived the mean abundances from fits to the integrated spectrum of the whole remnant. Further, note that some studies used a combination of regions on the rim and the interior of

 $^{^2}$ Note that both Kamitsukasa et al. (2015) and Zhang et al. (2019) work with mixed-morphology remnants whereas N132D has not been classified as one so far.

Table 7. As in Table 4, for ionizing and recombining plasma model fits for regions f1, f2, f3, f4, f5 and f6, which have weak signature of Fe K emission (see Figures 8, C.11, C.12, C.13, C.14 and C.15). Elemental abundances of respective model components not shown here are all frozen to average local LMC values (as in Table 6).

Model Parameter Units Region f1 Region f2 N_{H} 10 ²² cm ⁻² 0.09 ⁴⁰ 01 0.16 ⁴⁰ 01 KT_{e} vnei 1 2.66 ^{40,23} 2.70 ^{40,11} Si 1.69 ^{40,01} 0.16 ^{40,01} 0.16 ^{40,01} kT_{e} vnei 1 2.57 ^{41,41} 6.95 ^{43,45} 1.50 ^{40,42} 2.59 ^{40,93} 1.50 ^{40,42} 0.74 ^{40,01} kT_{e} vnei 1 2.55 ^{40,53} 1.50 ^{40,42} kT_{e} vnei 1 10 ⁴¹ cm ⁻³ 2.55 ^{40,53} 0.71 ^{40,01} kT_{e} vnei 1 0.74 ^{40,01} 0.74 ^{40,01} 0.74 ^{40,01} Ne 0.98 ^{40,25} 0.71 ^{40,01} 0.74 ^{40,01} 0.74 ^{40,01} Ne 0.88 ^{40,25} 0.74 ^{40,01} <th></th> <th></th> <th>$\frac{\text{Region f5}}{0.18^{+0.01}}$ $1.75^{+0.01}_{-0.14}$ $1.75^{+0.03}_{-0.14}$ \dots $1.75^{+0.45}_{-0.45}$ $0.79^{+0.43}_{-0.33}$</th> <th>Region f6 0.15^{+0.01}</th> <th>Model</th> <th></th> <th></th> <th></th> <th></th> <th></th> <th></th> <th></th>			$\frac{\text{Region f5}}{0.18^{+0.01}}$ $1.75^{+0.01}_{-0.14}$ $1.75^{+0.03}_{-0.14}$ \dots $1.75^{+0.45}_{-0.45}$ $0.79^{+0.43}_{-0.33}$	Region f6 0.15 ^{+0.01}	Model							
Immeter Units Region f1 $10^{22} \mathrm{cm}^{-2}$ $0.09^{40.01}_{-0.01}$ vnei 1 keV $2.66_{-0.29}^{40.01}$ vnei 1 keV $2.64_{-0.29}^{40.01}$ mei 1 $1.0^{21} \mathrm{cm}^{-3}$ $3.27_{-1.44}^{-4.14}$ mei 1 $1.0^{11} \mathrm{cm}^{-3}$ $4.84_{-1.59}^{-1.56}$ mei 1 $10^{-1} \mathrm{cm}^{-3}$ $4.84_{-1.59}^{-1.56}$ vnei 2 \dots $2.59_{-0.26}^{-0.02}$ vnei 1 $10^{-1} \mathrm{cm}^{-3}$ $4.84_{-1.59}^{-1.56}$ vnei 2 \dots $0.84_{-0.02}^{-0.02}$ m vnei 1 $10^{-1} \mathrm{cm}^{-3}$ $0.84_{-0.02}^{-0.02}$ m vnei 2 \dots $0.84_{-0.02}^{-0.02}$ m vnei 2 \dots $0.84_{-0.02}^{-0.02}$ m vnei 2 \dots $0.52_{-0.02}^{-0.02}$ m vnei 2 $10^{-1} \mathrm{cm}^{-3}$ $3.47_{-0.03}^{-0.03}$			Region f5 0.18 ^{-0.01} 1.75 ^{-0.01} 1.75 ^{-0.14} 1.75 ^{-0.45} 0.79 ^{-0.43}	Region f6 0.15 ^{+0.01}	Parameter							
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$			$\begin{array}{c} 0.18^{+0.01}_{-0.01}\\ 1.75^{+0.03}_{-0.14}\\ \dots\\ \dots\\ 1.75^{+0.56}_{-0.45}\\ 0.79^{+0.43}_{-0.45}\\ 0.79^{+0.43}_{-0.43}\end{array}$	$0.15\substack{+0.01\\-0.01}$		Units	Region f1	Region f2	Region f3	Region f4	Region f5	Region f6
vneil keV $2.66_{-0.29}^{-0.29}$ $3.27_{-1.14}^{-1.14}$ $3.27_{-0.08}^{-1.03}$ $2.59_{-0.08}^{-0.08}$ $2.59_{-0.08}^{-0.08}$ $2.559_{-0.08}^{-0.08}$ $2.559_{-0.08}^{-0.08}$ $2.59_{-0.08}^{-0.08}$ $2.56_{-0.08}^{-0.08}$ $2.56_{-0.08}^{-0.08}$ $2.59_{-0.09}^{-0.08}$ $2.59_{-0.08}^{-0.08}$ $0.76_{-0.01}^{-0.08}$ $0.84_{-0.01}^{-0.06}$ $0.88_{-0.25}^{-0.25}$ $0.88_{-0.25}^{-0.25}$ $0.52_{-0.25}^{-0.26}$ $0.52_{-0.25}^{-0.26}$ $0.45_{-0.06}^{-0.06}$ $0.45_{-0.06}^{-0.06}$ $0.45_{-0.06}^{-0.06}$ $0.45_{-0.06}^{-0.06}$ $0.45_{-0.06}^{-0.06}$ $0.45_{-0.06}^{-0.06}$			1.75 ^{+0.03} 1.75 ^{+0.56} 0.79 ^{+0.43} 0.79 ^{+0.43}		N _H	$10^{22}{ m cm}^{-2}$	$0.09^{+0.01}_{-0.01}$	$0.15^{+0.01}_{-0.01}$	$0.16^{+0.01}_{-0.01}$	$0.15_{-0.01}^{+0.01}$	$0.18^{+0.01}_{-0.01}$	0.15+0.01
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$			$\begin{array}{c}\\ 1.75_{-0.45}^{+0.56}\\ 0.79_{-0.35}^{+0.43}\end{array}$	$1.45_{-0.04}^{+0.06}$	<i>kTe</i> vrnei	keV	$1.97^{+0.21}_{-0.21}$	$1.33_{-0.17}^{+0.16}$	$1.27^{+0.08}_{-0.07}$	$2.06_{-0.39}^{+0.45}$	$1.54_{-0.13}^{+0.19}$	1.45 ^{+0.04}
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$			$1.75^{+0.56}_{-0.45}$ $0.79^{+0.43}_{-0.35}$:	kT_init vrnei	keV	10	10	10	10	10	¦A¥ ≘
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$			$0.79^{+0.43}_{-0.35}$	$1.02\substack{+0.16\\-0.15}$	Si	:	$3.17^{+0.94}_{-0.82}$	$2.64_{-0.95}^{+1.42}$	$0.91\substack{+0.16\\-0.10}$	$3.05^{+1.64}_{-0.88}$	$1.71_{-0.34}^{+0.29}$	$1.03^{+0.18}_{-0.14}$
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$				$0.73_{-0.14}^{+0.15}$	s	:	$1.66_{-0.66}^{+0.80}$	$0.39_{-0.04}^{+0.64}$	$0.39_{-0.15}^{+0.15}$	$2.72^{+1.49}_{-0.86}$	$0.91\substack{+0.30\\-0.28}$	$0.56_{-0.16}^{+0.17}$
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$			$0.61^{+0.15}_{-0.18}$	$0.47\substack{+0.07\\-0.11}$	Fe	:	$2.11_{-0.42}^{+0.50}$	$0.78_{-0.29}^{+0.38}$	$0.49\substack{+0.13\\-0.06}$	$1.67\substack{+0.72\\-0.19}$	$0.56_{-0.12}^{+0.13}$	$0.43^{+0.06}_{-0.07}$
Im vneil 10 ⁻⁴ cm ⁻⁵ 1.67 ^{0.37} /1.028 vneil 2 keV 1.04 ^{0.08} /0.04 vneil keV 1.04 ^{0.08} /0.04 0.04 1.65 ^{0.05} /0.05 0.98 ^{0.02} /0.05 0.88 ^{0.02} /0.05 0.85 ^{0.02} /0.06 0.52 ^{0.016} /0.00 0.45 ^{0.006} /0.00 neil 10 ¹¹ cm ⁻³ s 3.47 ^{0.036} /0.00 m vneil 10 ⁻⁴ cm ⁻⁵ 8.16 ^{0.033} /0.03			$5.50^{+3.14}_{-1.52}$	$6.27^{+5.13}_{-2.64}$	au vrnei	$10^{11}{ m cm^{-3}~s}$	$5.93_{-2.12}^{+6.40}$	$2.20^{+0.45}_{-0.49}$	$4.52_{-0.44}^{+0.64}$	$4.97^{+5.34}_{-2.09}$	$6.43^{+3.25}_{-2.15}$	7.71+3.01 50
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$			$7.49^{+1.36}_{-1.01}$	$16.49^{+1.42}_{-1.62}$	norm vrnei	$10^{-4}{\rm cm}^{-5}$	$2.73^{+0.34}_{-0.30}$	$8.60^{+3.83}_{-3.16}$	$34.31_{-5.09}^{+8.59}$	$2.84^{+1.28}_{-0.52}$	$9.33^{+1.88}_{-1.38}$	$13.48^{+1.86}_{-1.23}$
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	01 U.92-0.03		$0.87^{+0.04}_{-0.03}$	$0.88^{+0.02}_{-0.02}$	kTe vnei	keV	$1.02\substack{+0.03\\-0.02}$	$0.74_{-0.01}^{+0.02}$	$0.90^{+0.04}_{-0.03}$	$0.89_{-0.03}^{+0.03}$	$0.86_{-0.03}^{+0.03}$	0.89 ^{+0.04} A
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	$06 0.89^{+0.15}_{-0.13}$		$0.83^{+0.18}_{-0.08}$	$1.31_{-0.20}^{+0.22}$	Ne	:	$1.91^{+0.85}_{-0.60}$	$1.00^{+0.24}_{-0.12}$	$1.40^{+1.65}_{-0.28}$	$0.74_{-0.08}^{+0.09}$	$0.83_{-0.09}^{+0.08}$	$1.36_{-0.24}^{+0.14}$ O
$\begin{array}{c ccccc} & \cdots & 0.85^{+0.25}_{+0.16} \\ & \cdots & 0.52^{+0.22}_{+0.17} \\ & \cdots & 0.45^{-0.06}_{-0.06} \\ & \cdots & 0.45^{-0.06}_{-0.06} \\ & \cdots & 0.47^{+0.26}_{-0.23} \\ & \text{rm vnei 2} & 10^{-4}\mathrm{cm}^{-5} & 8.16^{+0.73}_{-0.33} \\ & \text{rm vnei 2} & 10^{-4}\mathrm{cm}^{-5} & 8.16^{+0.73}_{-0.33} \\ \end{array}$	$0.68^{+0.06}_{-0.07}$		$0.70_{-0.08}^{+0.07}$	$0.98^{+0.08}_{-0.10}$	Mg	÷	$1.15_{-0.15}^{+0.25}$	$0.90^{+0.23}_{-0.12}$	$1.21^{+2.27}_{-0.30}$	$0.54_{-0.02}^{+0.04}$	$0.71^{+0.05}_{-0.07}$	$0.99^{\pm0.23}_{-0.13}$
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	$05 0.71^{+0.07}_{-0.06}$		$0.64_{-0.09}^{+0.05}$	$0.82\substack{+0.13\\-0.04}$	Si	:	$0.98_{-0.10}^{+0.12}$	$0.81\substack{+0.21\\-0.11}$	$1.41_{-0.43}^{+4.32}$	$0.57_{-0.09}^{+0.10}$	$0.67_{-0.11}^{+0.06}$	$0.88^{+0.09}_{-0.13}$
$\begin{array}{c cccc} & & 0.45^{+0.10}_{-0.06} \\ & & & 0.45^{+0.10}_{-0.06} \\ & & & 10^{11} \mathrm{cm}^{-3} \mathrm{s} & 3.47^{+0.30}_{-0.30} \\ & & & & \mathrm{rm} \mathrm{vnei} 2 & 10^{-4} \mathrm{cm}^{-5} & 8.16^{+0.73}_{-0.33} \\ & & & \mathrm{rm} \mathrm{vnei} 2 & 10^{-4} \mathrm{cm}^{-5} & 8.16^{+0.73}_{-0.33} \end{array}$	$09 0.65^{+0.11}_{-0.11}$		$0.47^{+0.14}_{-0.17}$	$0.62\substack{+0.37\\-0.30}$	S	:	$0.67\substack{+0.18\\-0.17}$	$0.94_{-0.13}^{+0.10}$	$1.52_{-0.20}^{+0.47}$	$0.49_{-0.05}^{+0.12}$	$0.54_{-0.08}^{+0.13}$	2D 91.0+26.0
$\frac{10^{11} \text{ cm}^{-3} \text{ s} 3.47^{+0.35}_{-0.30}}{10^{-4} \text{ cm}^{-5} 8.16^{+0.73}_{-0.33}}$	$02 0.38^{+0.03}_{-0.03}$		$0.40^{+0.06}_{-0.04}$	$0.41\substack{+0.07\\-0.03}$	Fe	:	$0.51\substack{+0.04\\-0.04}$	$0.50_{-0.07}^{+0.08}$	$0.76^{+3.64}_{-0.28}$	$0.32_{-0.03}^{+0.05}$	$0.42_{-0.04}^{+0.02}$	$0.55_{-0.06}^{+0.11}$
$10^{-4} \mathrm{cm}^{-5}$ $8.16^{+0.73}_{-0.33}$	$27 2.51^{+0.28}_{-0.14}$		$2.88^{+0.31}_{-0.37}$	$2.7^{+0.19}_{-0.17}$	au vne i	$10^{11}{\rm cm^{-3}~s}$	$3.49^{+1.11}_{-0.70}$	$3.39_{-0.33}^{+0.37}$	$2.10^{+0.24}_{-0.26}$	$2.16_{-0.29}^{+0.40}$	$2.79^{+0.11}_{-0.11}$	$2.88^{\pm 0.43}_{-0.36}$
	$\frac{.61}{.49}$ 40.16 $\frac{+3.22}{-2.64}$		$22.63^{+3.79}_{-4.10}$	$18.21^{+1.08}_{-0.49}$	norm vnei	$10^{-4} {\rm cm}^{-5}$	$7.14_{-0.45}^{+0.31}$	$25.64_{-4.79}^{+4.48}$	$18.43_{-10.22}^{+8.17}$	$21.31_{-2.21}^{+0.59}$	$21.57^{+2.22}_{-2.05}$	$18.63^{+3.26}_{-2.88}$
kT_e vpshock keV $0.59_{-0.04}^{+0.03}$ $0.38_{-0.07}^{+0.02}$	$0.49^{+0.03}_{-0.03}$		$0.53_{-0.05}^{+0.05}$	$0.51\substack{+0.05\\-0.04}$	kTe vpshock	keV	$0.59_{-0.01}^{+0.01}$	$0.38_{-0.08}^{+0.03}$	$0.49^{+0.04}_{-0.06}$	$0.45_{-0.03}^{+0.05}$	$0.52_{-0.06}^{+0.05}$	$0.52^{+0.06}_{-0.03}$
τ vpshock 10^{11} cm ⁻³ s $4.14^{+0.26}_{-0.26}$ $6.33^{+2.97}_{-1.22}$	$4.90^{+0.55}_{-0.42}$		$5.27^{+0.38}_{-0.38}$	$3.10^{+0.46}_{-0.36}$	au vpshock	$10^{11}{ m cm^{-3}~s}$	$4.09_{-0.25}^{+0.30}$	$6.37^{+1.90}_{-1.69}$	$4.85^{+1.04}_{-0.79}$	$4.98^{+1.50}_{-1.22}$	$5.26_{-0.59}^{+0.77}$	$3.29_{-0.43}^{+0.57}$
norm vpshock $10^{-4} \mathrm{cm}^{-5}$ $12.09^{+0.40}_{-0.67}$ $21.10^{+4.31}_{-2.47}$	$\frac{31}{47}$ 31.76 $^{+1.36}_{-1.46}$		$19.63^{+1.72}_{-2.90}$	$16.20^{+1.69}_{-0.78}$	norm vpshock	$10^{-4} {\rm cm}^{-5}$	$11.72_{-0.69}^{+0.73}$	$21.74_{-1.40}^{+2.36}$	$31.16^{+1.94}_{-1.81}$	$23.65^{+1.61}_{-1.69}$	$19.18\substack{+2.48\\-1.87}$	$17.02^{+1.76}_{-1.40}$
cstat(0)/dof 1126/966 1048/966	966 1190 / 966	1110/966 1	1173 / 966 1	1135 / 966	cstat(0)/dof	÷	1110/966	1042 / 966	1182/966	1110/966	1171/966	1126 / 966
cstat(E) $\pm \sigma_{\rm E}$ 1018 ± 45 1018 ± 46	46 1039 ± 49	1017 ± 45 1	1025 ± 48 1	1018 ± 45	cstat (E) $\pm \sigma_{\rm E}$	÷	1021 ± 45	1010 ± 46	1038 ± 47	1017 ± 45	1025 ± 47	1014 ± 45

the remnant; 2 out of 8 regions used by Schenck et al. (2016) and 2 out of the 4 regions used by Dopita et al. (2018) are in the interior. For the results from Dopita et al. (2018)/Korn et al. (2002) that are derived from observations with the ANU Wide-Field Spectrograph (WiFeS, Dopita et al. 2010), we average over the four brightest clouds (in the optical) that were used to determine the abundances. There is no uncertainty on the abundance of Mg local to N132D because it could not be constrained from the data used and was fixed to half of the solar value. For Fe, spectral fits to the four brightest clouds returned the same value. The measurements from Dopita et al. (2019) are from the same regions as in Dopita et al. (2018), but with an improved shock modeling code that takes into account the emission from the photoionization region ahead of the forward shock. The quoted abundances of Mg, Si and Fe from Dopita et al. (2019) are the values assumed by the authors in the model.

The values in parenthesis that we quote from Hughes et al. (1998) and Schenck et al. (2016) represent abundances averaged over multiple SNRs in the LMC, the ones we take from Russell & Dopita (1992) are averaged over SNRs as well as supergiants, and those from Dopita et al. (2018)/Korn et al. (2002) are determined from N132D and B-stars in NGC 2004. The ones we report from Dopita et al. (2019) in the parenthesis are averaged over SNRs, B stars, F-supergiants and H II regions. Different studies have also used different observations to compute the mean abundances local to N132D, as we show in Table 8. The effect of dust depletion is only accounted for by Dopita et al. (2018) and Dopita et al. (2019), although the effects of depletion in different phases and shock conditions are largely unknown (see, for example, Williams et al. 2006; Maggi et al. 2019). For our work, we find the error and scatter of the fitted abundances using the method of Multiple Imputations (Lee et al. 2011) which takes into account the statistical as well as systematic uncertainties on the parameters (see Appendix B for further details). We suspect that the abundance of S is not well constrained due to the low number of S counts on the rim; this is also apparent in its relatively large 1σ uncertainty.

Our measurements that are local to N132D match closely with Blair et al. (2000), except for Mg and S, however, the abundance of Mg reported in Blair et al. (2000) is classified as a lower limit by the authors whereas that of S is within the uncertainty. Our measurements of Ne and Mg are higher and lower, respectively, than the measurements of Dopita et al. (2018)/Korn et al. (2002), however they are in good agreement with those of Dopita et al. (2019). As compared to Maggi et al. (2016), we measure consistent (within the uncertainties) abundances of Ne, Si and Fe. There is a significant discrepancy of \sim 1.0 dex between the abundance of O measured by Maggi et al. (2016) and other works including ours. We note that we have adopted the best-fit abundance values for the CSM/ISM model component for N132D from Table E.2 of Maggi et al. (2016) whereas the majority of the O emission is fitted by the hotter, O-rich model component in their model.

Similarly, we can compare our results with that of Schenck et al. (2016), especially because the same archival *Chandra* data have been used in both the studies. It is worth noting that our measurements of the abundances of O, Ne and Mg are 0.4 dex higher whereas those of Si and Fe are in excellent agreement with that of Schenck et al. (2016). We speculate that the reason for this discrepancy can be that our measurements are derived from fitting the entire rim whereas those of Schenck et al. (2016) come from fitting certain regions located on different parts of the rim as well as some regions in the interior. In fact, we find that some of the regions on the rim analyzed by Schenck et al. (2016) have systematically lower abundances than the average in our fits to the same regions (regions r13-r15).

5.2. Shock Velocity and Electron Density

We calculate the forward shock velocity and an estimate of the shock age along the rim using average physical conditions of the plasma (temperature and ionization timescale), geometry of the region and its norm. Using the Rankine-Hugoniot conditions which predict mass proportional heating for electrons and ions (Landau & Lifshitz 1975; Berezhko & Ellison 1999; Vink 2012) and assuming no energy losses (for example, due to cosmic rays), we can relate the electron temperature to the shock velocity as

$$kT_e \approx \frac{3}{16} m_\mu v_{\rm s}^2, \qquad (1)$$

where m_{μ} is the mean mass per free particle and v_s is the shock velocity. Assuming the majority of the electrons are contributed by H and He, $m_{\mu} \sim 0.59 \,\mathrm{m_H}$. The mean electron temperature we find from our analysis of the rim regions is $\langle kT_e \rangle = 0.85 \pm 0.20 \text{ keV}$ (see Table 6). Then the mean shock velocity of the blast wave is $\langle v_s \rangle = 855 \pm 100 \,\mathrm{km \, s^{-1}}$. We estimate the average shock age (by finding the electron density n_e using the norm and the 3D geometrical approximation described in Appendix D) to be $\langle \tau \rangle = (1200 \pm 270) f^{-1/2}$ yr for the rim, where f denotes the volume filling factor of the shell region. Filling factor refers to the fraction of emitting plasma filling a volume in the remnant and is a parameter to account for our lack of knowledge about the extent of the emitting volume that is filled with X-ray emitting plasma (Higdon & Lingenfelter 1980). Table 9 lists the corresponding shock velocities, electron densities and shock ages we find for all the rim regions.

Through simulations of a blast wave evolving into a cavity and colliding with clouds, Tang et al. (2016) propose that the shock velocity is decreased by roughly $\sqrt{n_e}$ when the blast wave hits the clouds. For the mean shock velocity (855 ±

		ber of regions within The second row denote		•				t to the integrated s	pectrum of the
Element	Solar ^a	Russell and Dopita ^b	Hughes ^c	Blair ^d	Schenck ^e	Maggi ^f	Dopita/Korn ^g	Dopita19 ^h	This Work

Table 8. Comparison of mean abundances local to N132D with other works. Values in parenthesis denote those averaged over many SNRs in the LMC. The first row

WW18W4419ASCAHSTChandraXMM-NewtonWiFeSWiFeSChandraO8.69[8.35±0.06]8.14±0.06 [8.21±0.07]8.45±0.107.97±0.09 [8.04±0.04] $7.39^{+0.17}_{-0.09} [8.01^{+0.14}_{-0.21}]$ 8.31^{+0.01}_{-0.03} [8.32±0.06]8.32±0.04 [8.40±0.05]8.39±0.19Ne7.94[7.61±0.05]7.56±0.06 [7.55±0.08]7.64±0.107.29±0.06 [7.39±0.06]7.60±0.02 [7.39^{+0.11}_{-0.13}]7.44^{+0.01}_{-0.03} [7.52±0.09]7.62±0.04 [7.70±0.09]7.71±0.12Mg7.40[7.47±0.13]7.08±0.07 [7.08±0.07]6.75±0.106.73±0.07 [6.88±0.06]6.68±0.02 [6.92^{+0.20}_{-0.37}]7.47 [7.37±0.06]7.19 [7.19±0.09]7.08±0.15Si7.27[7.81]7.08±0.13 [7.04±0.08]7.00±0.107.00±0.07 [6.99±0.11]6.86±0.03 [7.11^{+0.21}_{-0.41}][7.10±0.07]7.11 [7.11±0.04]7.03±0.18S7.09[6.70±0.09]6.73±0.06 [6.71]6.63±0.107.01 ^{+0.09} _{-0.06} [7.00±0.15]7.10±0.07 [6.93±0.05]6.95±0.31Fe7.43[7.23±0.14]7.08±0.06 [7.01±0.11]6.85±0.106.97±0.07 [6.84±0.05]6.88±0.02 [6.97 ^{-0.13} _{-0.13}]7.23 [7.33±0.03]7.33 [7.33]6.96±0.15	Element	Solar ^a	Russell and Dopita ⁰	Hughes	Blair ^a	Schenck ^e	Maggi ¹	Dopita/Korn ^g	Dopita19 ⁿ	This Work
O8.69 $[8.35\pm0.06]$ 8.14 ± 0.06 $[8.21\pm0.07]$ 8.45 ± 0.10 7.97 ± 0.09 $[8.04\pm0.04]$ $7.39^{+0.17}_{-0.09}$ $[8.01^{+0.14}_{-0.21}]$ $8.31^{+0.01}_{-0.03}$ $[8.32\pm0.04]$ 8.32 ± 0.04 $[8.40\pm0.05]$ 8.39 ± 0.19 Ne7.94 $[7.61\pm0.05]$ 7.56 ± 0.06 $7.55\pm0.08]$ 7.64 ± 0.10 7.29 ± 0.06 7.60 ± 0.02 $[7.39^{+0.17}_{-0.15}]$ $7.44^{+0.01}_{-0.03}$ $[7.52\pm0.09]$ 7.62 ± 0.04 $[7.70\pm0.09]$ 7.71 ± 0.12 Mg7.40 $[7.47\pm0.13]$ 7.08 ± 0.07 $[7.75\pm0.10]$ 6.73 ± 0.07 $[6.88\pm0.06]$ 6.68 ± 0.02 $[6.29^{+0.20}_{-0.37}]$ 7.47 $[7.37\pm0.06]$ 7.19 $[7.19\pm0.09]$ 7.08 ± 0.15 Si7.27 $[7.81]$ 7.08 ± 0.13 $[7.00\pm0.10]$ 7.00 ± 0.07 $[6.99\pm0.11]$ 6.86 ± 0.03 $[7.11^{+0.20}_{-0.41}]$ $[7.10\pm0.07]$ 7.11 $[7.11\pm0.04]$ 7.03 ± 0.18 S7.09 $[6.70\pm0.09]$ 6.73 ± 0.06 6.3 ± 0.10 $7.01^{+0.09}_{-0.06}$ 7.10 ± 0.07 6.95 ± 0.31			W	W	1	8	W	4	4	19
Ne 7.94 [7.61\pm0.05] 7.56\pm0.06 [7.55\pm0.08] 7.64\pm0.10 7.29\pm0.06 [7.39\pm0.06] 7.60\pm0.02 [7.39\pm0.12] 7.44\pm0.01 +0.03 +0.05 +0.09 +0.04 +0.00 +0.02 +0.09 +0.15 +0.00 +0.02 +0.09 +0.015 +0.00 +0				ASCA	HST	Chandra	XMM-Newton	WiFeS	WiFeS	Chandra
Mg 7.40 $[7.47\pm0.13]$ 7.08 ± 0.07 6.75 ± 0.10 6.73 ± 0.07 $[6.88\pm0.06]$ 6.68 ± 0.02 $[6.92_{-0.37}^{+0.20}]$ 7.47 $[7.37\pm0.06]$ 7.19 $[7.19\pm0.09]$ 7.08 ± 0.15 Si 7.27 $[7.81]$ 7.08 ± 0.13 $[7.00\pm0.10]$ 7.00 ± 0.07 $[6.99\pm0.11]$ 6.86 ± 0.03 $[7.10\pm0.07]$ 7.11 $[7.11\pm0.04]$ 7.03 ± 0.18 S 7.09 $[6.70\pm0.09]$ 6.73 ± 0.06 $[6.3\pm0.10]$ $7.01_{-0.06}^{+0.09}$ 7.10 ± 0.07 6.95 ± 0.31	0	8.69	$[8.35 \pm 0.06]$	$8.14{\pm}0.06~[8.21{\pm}0.07]$	8.45 ± 0.10	$7.97{\pm}0.09$ [$8.04{\pm}0.04$]	$7.39_{-0.09}^{+0.17} \ [8.01_{-0.21}^{+0.14}]$	$8.31^{+0.01}_{-0.03}$ [8.32 ± 0.06]	$8.32{\pm}0.04$ [$8.40{\pm}0.05$]	8.39 ± 0.19
Si 7.27 [7.81] 7.08 ± 0.13 7.00 ± 0.10 7.00 ± 0.07 $[6.99 \pm 0.11]$ 6.86 ± 0.03 $[7.10 \pm 0.07]$ 7.11 $[7.11 \pm 0.04]$ 7.03 ± 0.18 S 7.09 $[6.70 \pm 0.09]$ 6.73 ± 0.06 $[6.71]$ 6.63 ± 0.10 $$ 7.01 ± 0.09 7.10 ± 0.07 6.95 ± 0.31	Ne	7.94	$[7.61 \pm 0.05]$	$7.56{\pm}0.06$ [$7.55{\pm}0.08$]	7.64 ± 0.10	$7.29{\pm}0.06$ [$7.39{\pm}0.06$]	$7.60{\pm}0.02~[7.39^{+0.11}_{-0.15}]$	$7.44^{+0.01}_{-0.03}$ [7.52 \pm 0.09]	$7.62{\pm}0.04$ [$7.70{\pm}0.09$]	7.71 ± 0.12
S 7.09 [6.70±0.09] 6.73±0.06 [6.71] 6.63±0.10 $7.01^{+0.09}_{-0.06}$ [7.00±0.15] 7.10±0.07 [6.93±0.05] 6.95±0.31	Mg	7.40	$[7.47 \pm 0.13]$	$7.08{\pm}0.07$ [$7.08{\pm}0.07$]	6.75 ± 0.10	6.73±0.07 [6.88±0.06]	$6.68 {\pm} 0.02$ [$6.92 {}^{+0.20}_{-0.37}$]	7.47 [7.37±0.06]	7.19 [7.19±0.09]	7.08 ± 0.15
	Si	7.27	[7.81]	$7.08{\pm}0.13$ [$7.04{\pm}0.08$]	7.00 ± 0.10	7.00±0.07 [6.99±0.11]	$6.86{\pm}0.03~[7.11^{+0.20}_{-0.41}]$	$[7.10 \pm 0.07]$	7.11 [7.11±0.04]	7.03 ± 0.18
Fe 7.43 [7.23 \pm 0.14] 7.08 \pm 0.06 [7.01 \pm 0.11] 6.85 ± 0.10 $6.97 \pm 0.07 [6.84 \pm 0.05]$ $6.88 \pm 0.02 [6.97^{+0.13}_{-0.18}]$ 7.23 [7.33 \pm 0.03] 7.33 [7.33] 6.96 ± 0.15	s	7.09	$[6.70 \pm 0.09]$	6.73±0.06 [6.71]	6.63 ± 0.10			$7.01^{+0.09}_{-0.06}$ [7.00±0.15]	$7.10{\pm}0.07$ [$6.93{\pm}0.05$]	6.95 ± 0.31
	Fe	7.43	[7.23±0.14]	7.08±0.06 [7.01±0.11]	6.85 ± 0.10	6.97±0.07 [6.84±0.05]	$6.88{\pm}0.02~[6.97{}^{+0.13}_{-0.18}]$	7.23 [7.33±0.03]	7.33 [7.33]	6.96 ± 0.15

NOTE—References: (a) Wilms et al. 2000; (b)Russell & Dopita 1992; (c) Hughes et al. 1998; (d) Blair et al. 2000; (e) Schenck et al. 2016; (f) Maggi et al. 2016; (g) Dopita et al. 2018; Korn et al. 2002; (h) Dopita et al. 2019.

Table 9. Shock velocity (v_s), electron density (n_e) and shock age (t) in rim regions, with 1σ errors. v_s is estimated from equation 1, and n_e from the norm and geometrical approximations described in Appendix D. Ionization timescales and electron density estimates are then used to calculate the age of the forward shock as $t = \tau/n_e$. The mean shock velocity is $\langle v_s \rangle = 855 \pm 100 \,\mathrm{km \, s^{-1}}$, electron density is $\langle n_e \rangle = (6 \pm 2) \, f^{-1/2} \,\mathrm{cm^{-3}}$ and shock age is $\langle t \rangle = (1200 \pm 270) \, f^{-1/2} \,\mathrm{yr}$, where f represents the volume filling factor.

Region ID	$v_s (km s^{-1})$	$n_e (f^{-1/2} \mathrm{cm}^{-3})$	$t (f^{-1/2} yr)$
r1	1029 ± 46	3 ± 1	680 ± 110
r2	893 ± 34	4 ± 1	1490 ± 380
r3	745 ± 17	7 ± 3	2620 ± 1020
r4	843 ± 15	5 ± 1	1130 ± 130
r5	784 ± 11	8 ± 2	1380 ± 160
r6	843 ± 57	7 ± 3	850 ± 300
r7	833 ± 21	7 ± 2	1220 ± 190
r8	774 ± 17	7 ± 1	760 ± 180
r9	779 ± 22	4 ± 3	1300 ± 260
r10	812 ± 43	5 ± 3	1990 ± 530
r11	950 ± 55	5 ± 2	990 ± 280
r12	917 ± 19	4 ± 1	1400 ± 190
r13	941 ± 32	4 ± 1	800 ± 290
r14	817 ± 21	6 ± 1	770 ± 170
r15	908 ± 48	5 ± 2	610 ± 180
r16	828 ± 21	6 ± 2	790 ± 90
r17	950 ± 37	3 ± 1	920 ± 190
r18	812 ± 16	8 ± 2	870 ± 100
r19	785 ± 11	7 ± 1	2400 ± 280

100 km s⁻¹) and electron density $(6 \pm 2 f^{-1/2} \text{ cm}^{-3})$ we derive, this implies a mean pre-collision blast wave velocity of ~ 2100 km s⁻¹ (if $f \sim 1$). This is in good agreement with the pre-collision velocity of 1900 km s⁻¹ proposed by Chen et al. (2003) for N132D, where the authors use a semi-analytical thin shell model to study an SNR crossing a density jump (a condition that can prevail in SNRs expanding in a low density cavity). For N132D, Chen et al. (2003) conclude that the current shock has been interacting with denser material for ~ 700 yr when it was slowed down to ~ 700 km s⁻¹ from its pre-collision value due to impact with the walls of the cavity in which the massive progenitor is thought to have exploded. Thus, the observations are consistent with a scenario in which this SNR exploded inside a cavity (in a denser surrounding medium) possibly created by the winds of its progenitor.

5.3. Deduction of Progenitor Mass

We estimate the mass of the progenitor with three different methods given in the literature using the spectral results from the interior regions.

5.3.1. Estimates from Nucleosynthesis Models

We can compare the yields obtained from the spectral fit of region e1 to models of low-metallicity CCSNe nucleosynthesis (Nomoto et al. 2006; Kobayashi et al. 2006)³ in order to deduce the mass of the progenitor, as was investigated by Blair et al. (2000, see their Table 10). As we point out in Section 3, this is the only region that shows enhanced abundances of 5/6 elements that we fit across the remnant. Since direct model yields for LMC metallicity ($Z_{LMC} = 0.008$) are not available in Nomoto et al. (2006) and Kobayashi et al. (2006), we take a geometric mean of model yields at SMC

³ Same models and corresponding yields are reported in Nomoto et al. (2006) and Kobayashi et al. (2006).

metallicities ($Z_{SMC} = 0.004$) and Milky Way ($Z_{MW} = 0.02$) to imitate the LMC environment. Kobayashi et al. (2011) updated the yields given by Kobayashi et al. (2006) for Z = 0.004; $18M_{\odot}$ and Z = 0.02; $25M_{\odot}$ models because the earlier models produced large amounts of ¹³C and N due to erroneous mixing of H into the He-burning layer, also affecting the yields of other elements. Accordingly, we use the updated yields for these two models in our calculations.

We use the Mahalanobis distance and L_1 norm methods to find the measure of closeness between our observed yields and the yields predicted by the models. The Mahalanobis distance (M_D)

$$M_{\rm D} = \sqrt{\sum_{i=1}^{n} \frac{(x_i - y_i)^2}{s_i^2}},$$
 (2)

is essentially an error (s_i) weighted Euclidean distance between the data (the test set x_i representing the observed yields from our work) and the various nucleosynthesis models (y_i) (Mahalanobis 1936). The model yields are given in solar masses. Thus, to compare them with the best-fit values from the spectral fit to region e1, we convert the latter to elemental yields by multiplying them with atomic mass, since the reference scale is defined for the number of atoms relative to H and not the atomic mass. The test set is best explained by that model set for which the Mahalanobis distance is a minimum. The L_1 norm method works on a similar principle of distance minimization; its logarithmic form is given by (for example, Dopita et al. 2018, 2019)

$$L_1 = \frac{\sum_{j=1}^{m} |\log_{10} \frac{x_i}{y_i}|}{m},$$
(3)

where m = no. of elements. Figure 9 shows the abundance ratios relative to O for the different models and the data⁴. Model abundance ratios with a large scatter across progenitor masses (Si/O and Fe/O) drive the mass estimate because they show larger differences than other ratios that have relatively less scatter (Ne/O and Mg/O). While the Mahalanobis distance and L_1 norm are guided by Si/O for lower progenitor masses, they are largely set by Fe/O for massive progenitors. We present the comparison of progenitor mass deduction using the two methods in Figure 10. It can be noticed that both M_D and L_1 norm pass through the same global minimum as one moves from lower to higher mass progenitor models. Thus, we find a progenitor mass of $M_p = 20 M_{\odot}$ to be the closest to our observed yields. The model yields we use are calculated for an explosion energy of 10⁵¹ erg. If the explosion energy for N132D was higher (Bamba et al. 2018), this will affect the comparison we make below because core collapse models are very sensitive to the production of ⁵⁶Ni that correlates with the explosion energy (Pejcha & Thompson 2015, see their Figure 20; Sukhold et al. 2016, see their Figure 17). In case the explosion energy was $> 10^{51}$ erg, it will produce more Fe (Kobayashi et al. 2006; Nomoto et al. 2013). Further, these models are also sensitive to the rotation rate of the progenitor (Maeder & Meynet 2000; Tominaga et al. 2007; Nomoto et al. 2013).

Note that our deduction assumes that the region contains pure ejecta, which is an ideal case. Nonetheless, the ratios are not particularly sensitive to contamination from sweptup ISM. We verify this by subtracting the local average ISM values for each abundance and finding that both methods still have global minima at $20M_{\odot}$ (see the dashed lines in Figure 10). Although we utilize all possible elemental ratios to derive this estimate, we only use the X-ray heated ejecta from a single region (that represents a tiny fraction of the remnant in projection) to estimate the progenitor mass in this manner. Thus, the yields in this region may not be representative of the entire remnant. However, in order to compare these yields against the CCSNe model yields, we require sufficiently high abundances of more than 3 elements to remove the degeneracy between models of diverse progenitor masses. Given the depth of the existing data, we find e1 to be the singular region which provides the most stringent constraints on these abundances. It is not surprising that we only find one eligible region for this analysis since such regions are difficult to extract because the remnant is dominated by swept-up ISM at the age of N132D. Given these caveats, it becomes clear why this technique is not sufficient to place robust constraints on the progenitor mass, and other avenues should be explored for the same.

5.3.2. Estimates from Enriched Fe/Si

Katsuda et al. (2018a) point out that the estimates from elemental abundance ratios other than Fe/O or Fe/Si are not good tracers of progenitor mass because they are not sensitive to the CO core mass of the progenitor. Keeping this in mind, we also estimate the mass of the progenitor only from the Fe/Si ratio. As noted by Katsuda et al. (2018a), this technique cannot account for the unshocked ejecta in the SNR that can alter the measured Fe/Si ratio (see, however, Hwang & Laming 2012 and DeLaney et al. 2014 where it is proposed for SNR Cas A that up to 90 per cent of its ejecta has already been shocked). A major advantage of only using the Fe/Si in our case is that apart from region e1, we can also use the Fe K regions since they show enhanced abundances of Fe/Si in the hottest model component that we assume comes largely from ejecta. Including these regions lets us cumulatively sample a large fraction of the remnant.

⁴ We note that the results do not change if we take abundance ratios with respect to Si instead of O, as is often done in such comparisons (for example, Kumar et al. 2014; Frank et al. 2015; Braun et al. 2019).

Table 10. Estimates of the progenitor mass based on equation 4 from Katsuda et al. (2018a) that depends on the Fe/Si ratio measured in the ejecta component in spectral models for the interior regions. Region e1 is only fit with a two-component (vnei+vpshock) model. Details of the estimation are present in Section 5.3.2.

Region ID	Ionizing Model	Recombining Model
e1	12.15^{+7}_{-4}	
f1	9.65^{+7}_{-3}	10.67^{+3}_{-3}
f2	20.01^{+6}_{-2}	19.02^{+8}_{-5}
f3	12.65^{+5}_{-2}	12.66^{+5}_{-2}
f4	11.59^{+9}_{-4}	12.48^{+7}_{-3}
f5	16.70^{+4}_{-4}	17.93^{+3}_{-3}
f6	14.31^{+3}_{-2}	15.35^{+2}_{-2}

We use the best-fit relation provided by Katsuda et al. (2018a) that the authors find by fitting revised progenitor mass estimates for several SNRs in the Milky Way and the Magellanic Clouds against Fe/Si measured from observations,

$$\frac{\text{Fe/Si}}{\text{Fe/Si}_{\odot}} = 1.13 \times \exp\left(\frac{4.8 - M_{\text{p}}}{10.6}\right). \tag{4}$$

Table 10 lists the progenitor mass estimates we derive from the spectral fits to regions e1 and f1-f6. We utilize the bestfit abundances of the highest electron temperature component in the ionizing and recombining models for these regions (see Section 4.2.2 and Table 7). The estimated masses from different regions lie between $10 - 20M_{\odot}$, with mean mass $\sim 15M_{\odot}$. The variation in the deduced progenitor mass from region to region provides some insight into the importance of sampling as much of the ejecta as possible and the relatively large uncertainties on the deduced masses reflect the limitation imposed by the statistical precision of the current data.

5.3.3. Estimates from Explosion in a Cavity Models

Finally, we also estimate the progenitor mass using the relation between the radius of the cavity (R_b) and the progenitor mass (M_p) proposed by Chen et al. (2013) for SNRs evolving in cavities in or near giant molecular clouds

$$p_5^{1/3} R_{\rm b} = \left[\alpha \left(\frac{M_p}{M_{\odot}} \right) - \beta \right] {\rm pc} \,, \tag{5}$$

where p_5 is the interclump pressure in units of $10^5 \text{ cm}^{-3} \text{ K}$ (assumed to be unity, see Blitz 1993; Chevalier 1999; Krumholz et al. 2009), and $\alpha = 1.22 \pm 0.05$ and $\beta = 9.16 \pm 1.77$ are derived from a linear regression. This assumes that the cavity was formed prior to the explosion by

stellar winds of main sequence OB stars (Hughes 1987) and does not take into account the effects of a Wolf-Rayet phase, if any, on the wind-blown bubble (Chevalier 2005). Although such CCSNe undergo significant mass loss prior to the explosion (Pastorello et al. 2008; Dwarkadas & Gruszko 2012; Milisavljevic et al. 2013; Kamble et al. 2016), its effect on the late-time dynamics when the blast wave interacts with the circumstellar shell has been shown to be of little importance (Patnaude et al. 2015, 2017). Thus, the predictions by explosion in a cavity models like this for SNRs older than a few centuries may not be affected by the pre-supernova mass loss (Katsuda et al. 2018a). Since the shock has been interacting with the cloud in the south for the last few 100 yr (Chen et al. 2003), we assume that the radius of the cavity roughly equals the radius of X-ray emission. Adopting $R_b = 12.5 \,\mathrm{pc}$, we derive $M_{\rm p} = 17.8 \pm 3.8 M_{\odot}$, in agreement with the progenitor mass we determine above.

Note that the interclump pressure in N132D will be more than the thermal pressure since additional pressure support can arise from turbulence and cosmic rays in dynamically active regions like supernova remnants (Mac Low et al. 2005; Jenkins & Tripp 2011; Welty et al. 2016; Herrera-Camus et al. 2017). The average thermal pressure in the ISM of the LMC is estimated to be $p_{5,th} = 0.1$ (Welty et al. 2016). If we use this value as a lower limit on the interclump pressure, the minimum progenitor mass we obtain for the same cavity size is $\sim 12M_{\odot}$, consistent with the results we summarize below in Section 5.3.4.

5.3.4. Summary of Progenitor Mass Estimates

Estimation from various different pathways (observational as well as theoretical) as we present above enables us to put a constraint on the progenitor mass. It is encouraging to find that the estimates of all three methods are within 2σ of each other. However, the results from nucleosynthesis yields and explosion in a cavity models favor a slightly more massive progenitor for N132D than the average estimated through the Fe/Si ratio. Nevertheless, our results suggest an intermediate mass ($M_p < 25 M_{\odot}$) progenitor for N132D, lower than the estimates of Blair et al. (2000) based on UV/optical data (30–35 M_{\odot}) and by France et al. (2009) based on *Cosmic Origins Spectrograph* (50⁺²⁵₋₁₅ M_{\odot}) observations of N132D.

Taking into account the uncertainties and systematic scatter in all the three methods listed above, we quote our estimate of the progenitor mass of N132D as $M_p = 15 \pm 5 M_{\odot}$, in line with the revised mass estimates of Katsuda et al. (2018a). This range of possible progenitor masses also overlaps with the suggested range of massive stars which can undergo a Wolf-Rayet phase in the LMC (Chevalier 1999), as has been expected for N132D (Sutherland & Dopita 1995). Comparing with earlier predictions, we find that our progenitor mass estimate lies at the lower limit of Hwang et al. (1993) where

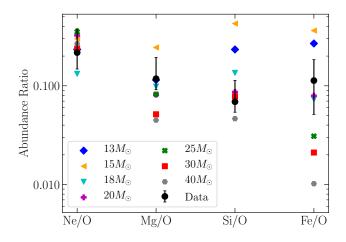


Figure 9. Abundances of different elements (relative to O) from the ejecta component of the best-fit model to the spectrum of region e1. Black markers denote the best-fit values and colored markers denote the nucleosynthesis yields for different progenitor masses from Nomoto et al. (2006); Kobayashi et al. (2006, 2011). The fit is present in Table 5 and the spectrum is shown in Figure 7.

the authors used *Einstein Observatory* data of N132D and nucleosynthesis models of Thielemann et al. (1992) to propose a progenitor mass of $20-25M_{\odot}$, whereas it is consistent with the estimate of slightly less than $20M_{\odot}$ given by Blair et al. (1994).

If the mass of the progenitor was indeed within $10-20M_{\odot}$, this will have important implications on the explosion in a cavity scenario as well as the lifetime of the Wolf-Rayet phase, if any (van Marle & Keppens 2012). A possible avenue to explore through simulations is to estimate the time and size of the creation of a cavity by pre-supernova winds for the estimated progenitor mass (Tenorio-Tagle et al. 1991; Garcia-Segura et al. 1996; Dwarkadas 2007; Patnaude et al. 2017), however, it is beyond the scope of this work.

5.4. High-Temperature Plasma and Fe K Emission

Emission in the 6.5–6.9 keV band can be mostly attributed to the presence of Fe He-like (Fe XXV) line emission⁵. *Suzaku* observations of N132D provide the centroid line energy of Fe K emission as $6656 \pm 9 \text{eV}$ (Yamaguchi et al. 2014) whereas *XMM-Newton* observations estimate it to be 6685^{+15}_{-14} eV (Maggi et al. 2016), proposed to be typical of

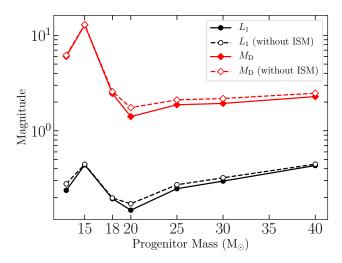


Figure 10. Magnitudes of L_1 Norm and Mahalanobis Distance (M_D) plotted against progenitor mass models, in order to deduce the progenitor mass of N132D by comparing its 'ejecta' yields with that given by the low-metallicity CCNSe nucleosynthesis models of Nomoto et al. (2006); Kobayashi et al. (2006, 2011). The source model we use to find the best-fit parameters is the vpshock+vnei model; see Table 5. Dashed curves use the residual of best-fit abundances after we subtract the local average ISM contribution, to check for swept-up ISM contamination.

middle-aged CCSNe (age > 2500 yr) evolving in dense CSM with high ambient densities (Yamaguchi et al. 2014; Patnaude et al. 2015). The Fe XXV He-like triplet spans about 64 eV between the Recombination and Forbidden lines. Thus, using the ionizing or recombining models affect the relative strengths of these lines in this complex, but with the limited statistics and spectral resolution of the ACIS data we are not sensitive to a shift in the centroid.

From both the ionizing (vnei + vnei + vpshock) and recombining (vrnei + vnei + vpshock) models we use to fit the six regions (see Table 7) containing Fe K emission, we establish that a hotter ($\gtrsim 1.5 \text{ keV}$) plasma is needed to explain the Fe K emission in this remnant, while not overproducing the flux from Fe L at lower energies. A similar observation was also made by Maggi et al. (2016). However, both the models are able to explain this emission through hot NEI ionizing and recombining components, respectively. This degeneracy arises due to the low number of counts in the hard X-ray band and the complex nature of the fit with many free parameters. Our results are consistent with the conclusions of the Suzaku + Hitomi investigation by Hitomi Collaboration et al. (2018) and the NuSTAR + Suzaku analysis by Bamba et al. (2018). However, we are able to sample smaller and more compact regions with Chandra than these studies to show that the Fe K emission is distributed throughout the southern half of the remnant (not concentrated in a single feature) and the plasma history is most likely different for different regions. Together with the enhanced abun-

 $^{^5}$ Fe XXVI (Fe Li-like ion) also has certain line energies in the range 6.5–6.7keV, however, its emissivity is lower by at least an order of magnitude as compared to Fe XXV and becomes comparable only at temperatures $\lesssim 1.3 \, keV$ while the component accounting for Fe K emission in both the ionizing and recombining models is $\gtrsim 1.5 \, keV$. Moreover, for there to be significant flux from Fe XXVI, a high ionization rate for the Li-like stage (high temperature) is required which cannot be possible near (optically thin coronal) equilibrium, not to mention that the process would anyway be unimportant in the recombining case. Thus, we can safely neglect the presence of significant flux from Fe Li like ions in this energy range.

21

dances we find in other regions, this provides some evidence for an asymmetric explosion. However, the current *Chandra* data for N132D are not deep enough to reconstruct the ejecta distribution with sufficient precision to conclude that the explosion was indeed asymmetric. An additional complication is the relatively large uncertainty in the explosion center for N132D, which is needed to constrain the ejecta distribution (Winkler & Petre 2007; Holland-Ashford et al. 2017; Katsuda et al. 2018b).

Although Fe K emission has been found in several SNRs in the LMC (Maggi et al. 2016, see their Table 2), the origin of a hotter plasma is not yet clear (see, for example, Park et al. 2005). Applying the Rankine-Hugoniot strong shock conditions to the individual species leads to mass-proportional heating, so $T_e \ll T_i$ (by the ratio m_e/m_i ; see, for example, Shimada & Hoshino 2000). Coulomb equilibration (many small angle scatterings) would give a characteristic equilibration timescale of ~ 6000 yr, too slow to account for electrons hot enough to excite X-ray emission lines. This argues for collisionless equilibration - collective scattering of electrons with plasma magnetic field fluctuations. The available evidence is that this is effective for slow ($\lesssim 500 \,\mathrm{km \, s^{-1}}$) shocks, but falls as roughly $\propto v_s^{-2}$ and is much less effective for fast shocks. For example, for the estimated forward shock velocity of 855 km s⁻¹ the ratio of electron to proton temperature is ≈ 0.2 (Ghavamian et al. 2007, 2013) indicating that the forward shock is unlikely to be the source of the Fe K emission. Presumably the reverse shock has a higher velocity into the ejecta with corresponding higher electron and ion temperatures than at the forward shock. For our fitted values of the temperature and ionization timescale, the RRC emission from Si and S would be weak. The Si and S RRCs would be stronger for lower plasma temperatures. We see no obvious RRC features for lower temperatures, so we can exclude that region of parameter space. Deeper observations may allow better constraints on anomalous line ratios for the He-like Fe, and RRCs for lighter ions.

The high column densities of all the Fe K regions except region f1 can be associated with the presence or absence of clumps of molecular clouds, respectively, as has been discussed for other SNRs interacting with molecular clouds (Banas et al. 1997; Lee et al. 2012; Slane et al. 2015; Matsumura et al. 2017; Sano et al. 2019). In fact, from Figure 2 of Dopita et al. (2018), we find that region f1 does not contain any prominent shocked ISM clouds as observed in the optical, which is expected for its low column density. Thus, the origin of a recombining plasma in this region, if any, can be correlated with thermal conduction only if we assume that the dense cloud(s) in this region have already been evaporated. If the recombining plasma is due to thermal conduction, one would expect it to be interacting with dense gas, which is likely the case for region f2. This analysis informs us of the spatially as well as spectrally diverse signatures of the plasma present in these regions that has evolved differently over time largely based on the surrounding environment. However, the origin of hot plasma that gives rise to the Fe K emission cannot be established from the available data.

6. SUMMARY

In this work, we have presented spatially resolved X-ray spectroscopy of N132D, the brightest SNR in the LMC, based on archival *Chandra* observations. By fitting the spectra of the entire well-defined rim of the remnant with a planeparallel shock model, we calculate the mean local abundances of O, Ne, Mg, Si, S and Fe (Table 8) and find that Ne, Mg, Si and Fe show no excess or depletion on the rim around their mean and the associated total (statistical+systematic) uncertainty, whereas we find evidence of enhanced O and S on the north-western and north-eastern rim, respectively. A faint blob protruding outside the western rim shows enhanced abundance of O, however, extended X-ray observations are needed to ascertain if this blob is in fact an O-rich ejecta clump moving ahead of the blast wave.

Using information from the rim regions, we derive a mean forward shock velocity $\langle v_s \rangle = 855 \pm 100 \,\mathrm{km \, s^{-1}}$ and electron density $\langle n_e \rangle = (6 \pm 2) \, f^{-1/2} \,\mathrm{cm^{-3}}$ where *f* is the volume filling factor. For $f \sim 1$, our findings agree with the conclusions of Chen et al. (2003) where the authors propose that the shock collided with the cavity wall (inside which the progenitor exploded) $\sim 700 \,\mathrm{yr}$ ago when it was slowed down from its precollision value of $\sim 1900 \,\mathrm{km \, s^{-1}}$. This is in line with the proposed explosion in a cavity scenario for this remnant, which partly comes from CO observations of molecular clouds in its surroundings (Banas et al. 1997; Sano et al. 2015).

We follow a mix of observational and theoretical approaches to estimate the mass of the progenitor of the remnant: 1. through comparison of best-fit ejecta abundances from region e1 with the nucleosynthesis model yields from Nomoto et al. (2006); Kobayashi et al. (2006, 2011), 2. from Fe/Si ratio measured in the ejecta components of multiple regions in the interior (Katsuda et al. 2018a), and 3. predictions from theoretical model of a core-collapse explosion in a cavity within a molecular cloud complex (Chevalier 1999; Chen et al. 2013). Our estimated progenitor mass of $15 \pm 5M_{\odot}$ is significantly lower than estimates based on optical data (Blair et al. 2000; France et al. 2009), but consistent with those of Katsuda et al. (2018a).

The presence of Fe K emission in N132D is well known (Behar et al. 2001; Xiao & Chen 2008; Yamaguchi et al. 2014; Maggi et al. 2016; Bamba et al. 2018; Hitomi Collaboration et al. 2018). With the spatial resolution of *Chandra*, we find that the Fe K complex emission is distributed largely across its southern half and is not located in a single feature. We fit the spectra of this emission in six regions using two

different models that have three components each. These two models have two components in common, which account for the shell emission (plane-parallel shock) and cooler, soft Xray emitting plasma (non-ionization equilibrium). The third component which accounts for the hotter, hard X-ray emitting plasma and Fe K emission is a non-equilibrium ionizing plasma in one model and a recombining plasma in the other model. In both the models, we find that a hot plasma $(\gtrsim 1.5 \text{ keV})$ is needed to explain the Fe K feature, and that this plasma is distinct from the soft x-ray emitting plasma. While our fits cannot distinguish between the ionizing and recombining plasma models for these regions because they result in similar fit statistics, we confirm the existence of such a hot plasma, in agreement with the findings of Bamba et al. (2018). A deeper observation and/or an observation with higher spectral resolution will help break the degeneracy between the two models and possibly shed light on the origin of the hot plasma and its interactions with molecular clouds in the region.

Thus, our analysis leads us to conclude that SNR N132D probably resulted from the core-collapse of an intermediate mass progenitor, in a cavity in the CSM created by presupernova winds. The exact type of the explosion, the possibility of a Wolf-Rayet phase prior to it, and the nature of the hot Fe K emitting plasma are some of the pertinent questions that still remain unanswered. Deeper observations with existing instruments and future observations with new instruments with enhanced capabilities will be required to address these questions.

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Facility: CXO (Weisskopf et al. 2000)

Software: CIAO (Fruscione et al. 2006), CALDB (Graessle et al. 2007), Xspec (Arnaud 1996), SAO ds9 (Joye & Mandel 2003), PINTofALE (Kashyap & Drake 2000), FTOOLS (Blackburn 1995), Matplotlib (Hunter 2007), Numpy (Oliphant 2006).

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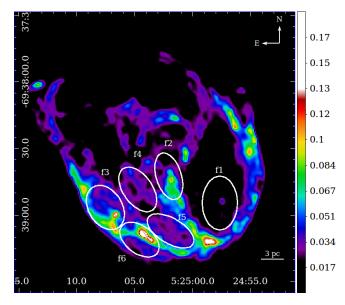


Figure A.1. Pileup map of SNR N132D from 2006 *Chandra* archival observations. The colorbar denotes the pileup fraction calculated in CIAO over all energies. The bright patches that are significantly affected by pileup in regions f2, f3 and f6 are excluded from the X-ray analysis.

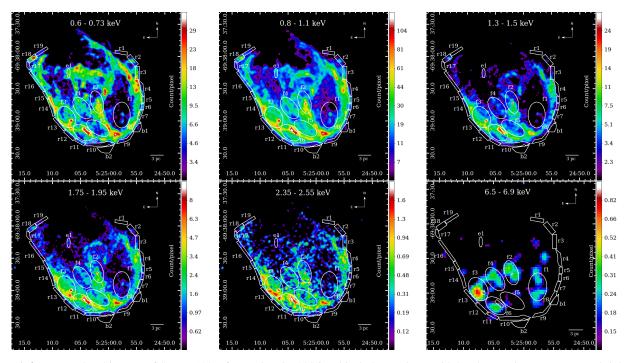


Figure A.2. Narrow band images of SNR N132D from *Chandra* 2006 archival observations, with bands covering (*Top*, L to R) brightest line emissions of O, Ne, Mg, and (*Bottom*, L to R) Si, S and Fe. All the images have been smoothed with a Gaussian kernel of radius 3, except for Fe where it has been binned by 4 and smoothed with a kernel of radius 3 owing to weak Fe K emission. Note that Fe also has numerous L-shell lines around 1 keV.

APPENDIX

A. PILEUP MAP AND NARROW BAND IMAGES

Figure A.1 shows the pileup fraction in the remnant. Note that CIAO estimates the pileup in an image without filtering over energy. Figure A.2 shows the narrow band images around various bright line emissions of O, Ne, Mg, Si, S and Fe in the remnant.

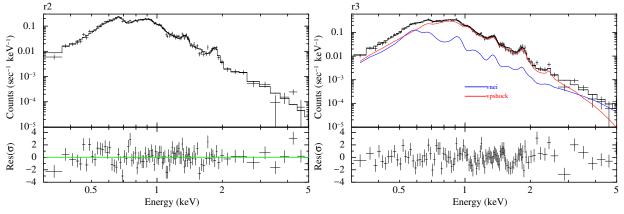


Figure C.1. Fits for regions r2 and r3 with the single vpshock and vnei+vpshock models, respectively.

B. ERROR AND SCATTER ON THE MEAN USING MULTIPLE IMPUTATIONS

We use the method of Multiple Imputations (Lee et al. 2011) to get an estimate of 68 per cent confidence intervals (similar to 1σ in the Gaussian case) for the mean values calculated for the blast wave spectral parameters across the rim of the remnant (viz., Table 6). This method incorporates systematic uncertainties caused by scatter amongst the best-fit values in different regions along with standard statistical uncertainties in the estimates of each parameter. Thus, it is a better descriptor of the scatter present in the samples. Further, it also lets us quantify the systematic variations of a parameter around the rim. We estimate the combined statistical and systematic uncertainty by computing the weighted average (see Section 3.1.2 of Lee et al. 2011) of the so-called between variance (*B*; the variance of the best-fit values and a measure of the systematic scatter present in the data) and the within variance (*W*; the average of the individual variances in each measurement, and a measure of the statistical quality of the data) as,

$$V = \mathbf{W} + \left(1 + \frac{1}{\mathbf{M}}\right)\mathbf{B}\,,\tag{B1}$$

where M are the number of regions, and \sqrt{V} represents the width of a t_{ν} -distribution with ν degrees of freedom,

$$\nu = (M-1) \left(1 + \frac{M \cdot W}{(M+1)B} \right)^2.$$
(B2)

The t_{ν} -distribution has inherently heavier tails than the Gaussian distribution, but closely approximates the width of the latter for large $\nu \gtrsim 7$. We compute a correction factor C_{ν} to map the 84th-percentile quantile of the t_{ν} -distribution to \sqrt{V} , and define a 1σ -equivalent error bar

$$\sigma_{\mu} = C_{\nu} \times \sqrt{V} \,. \tag{B3}$$

We find $\nu \in \{20, 79\}$ for the various parameters considered. The correction factor $C_{\nu} \rightarrow 1$ as $\nu \rightarrow \infty$, and is ≈ 2 per cent for $\nu = 20$. These 1σ -equivalent error bars are reported in Table 6.

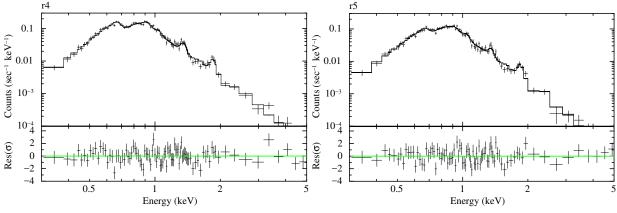
The separation of the statistical (W) and systematic (B) variances also allows us to explore when systematic variations are large compared to the accuracy with which the parameters are measured. Large values of the scatter, $\frac{\sqrt{B}}{\sqrt{W}}$, shows where systematic variations overwhelm the statistical error (see Table 6). When scatter > 1, it signifies that there is more systematic than statistical uncertainty in the parameter value. We consider all abundance samples where this threshold is exceeded as showing localized enhancements.

C. SPECTRAL FITS

Figures C.1 to C.10 display the spectral fits and residuals for rim regions with the vpshock model (regions r2, r4-r9, r11-r19, b1 and b2) and the vnei+vpshock model (regions r3 and r10). Figures C.11 to C.15 present the spectral fits for the Fe K regions. Note that the spectral counts in all the plots have been rebinned for display purposes.

D. ELECTRON DENSITY CALCULATION

For thermal plasma models, the Xspec normalization, norm, is proportional to emission measure as norm $\propto \int dV n_e n_{\rm H} \sim \langle n_e^2 \rangle f \Delta V$. Here, we assume $n_e \sim 1.2 n_{\rm H}$ (see, for example, Schenck et al. 2014; however, this will be a lower limit if considerable





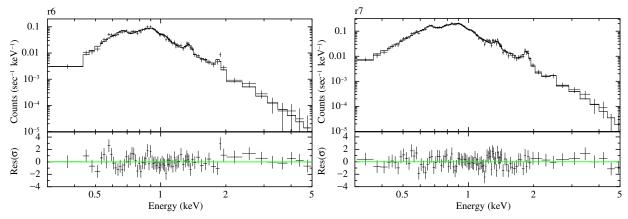
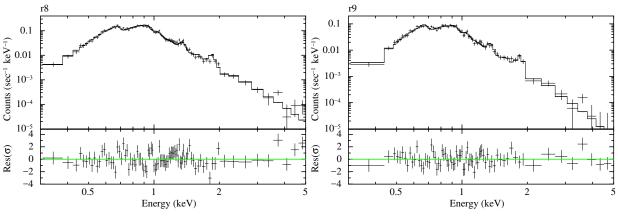


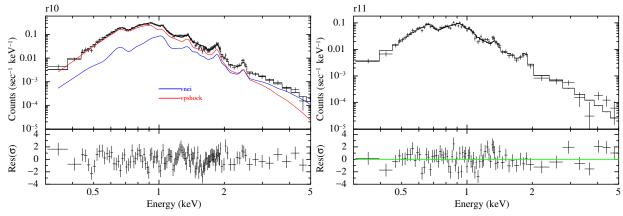
Figure C.3. Fits for regions r6 and r7 with the single vpshock.

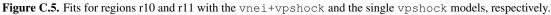




quantity of metals is present), $\langle n_e^2 \rangle$ is an average n_e^2 , f is the volume filling factor for the emitting region, and ΔV is the volume corresponding to the extraction region, *i.e.*, the projected area, A = wh, where w and h are the width and height of the extraction region, times an average line-of-sight depth, $\langle l \rangle$. To estimate the volume, some assumption is needed about the local three-dimensional structure. If the extraction region is assumed to be locally a projection through a figure of revolution with axis in the plane of the sky (see Figure D.1), the cross-sectional area can be expressed as

$$A_{\rm c} = R^2 \cos^{-1}\left(\frac{R-w}{w}\right) - (R-w)\sqrt{2Rw-w^2},$$
 (D4)





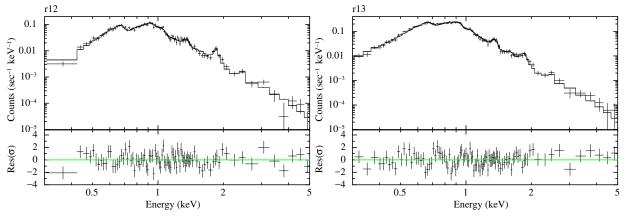
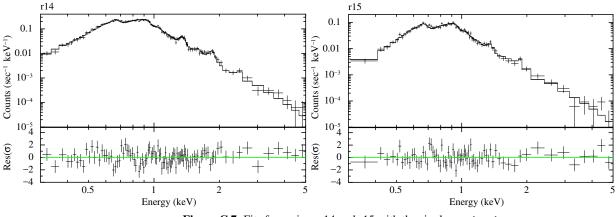
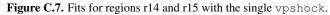
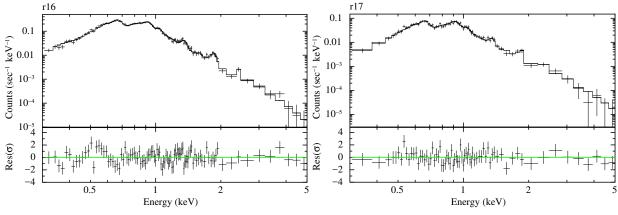


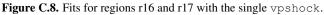
Figure C.6. Fits for regions r12 and r13 with the single vpshock.

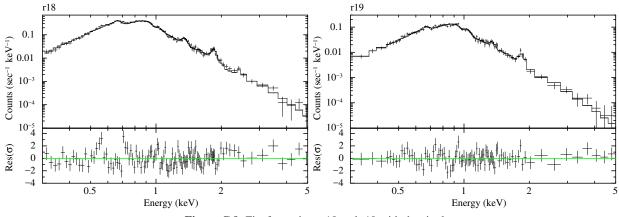




where *R* is the radius of the circular segment of width *w*. The average line-of-sight depth $\langle l \rangle$ can then be estimated by dividing this area by the width *w* of the extraction region, and the volume is then estimated by $\langle l \rangle$ times the area of the extraction region. Thus, $n_e \sim \langle 1.2 n_e^2 \rangle^{1/2} \sim 1106 \left(\text{norm} / f \Delta V \right)^{1/2} \text{ cm}^{-3}$, where norm is in units of cm⁻⁵, and ΔV is in units of pc³.









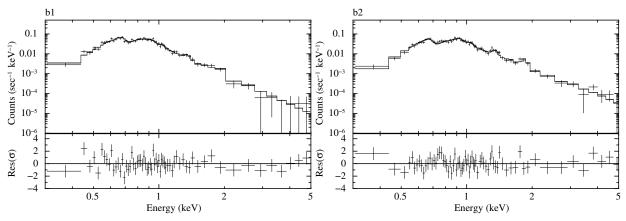
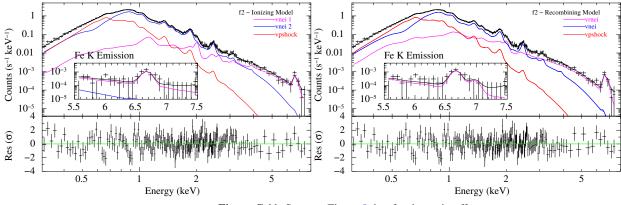
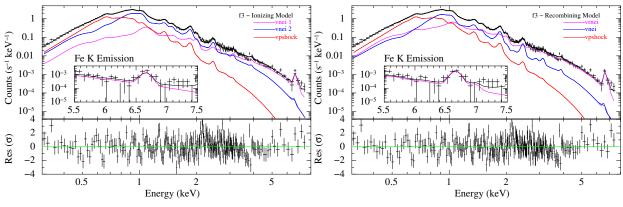
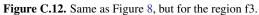


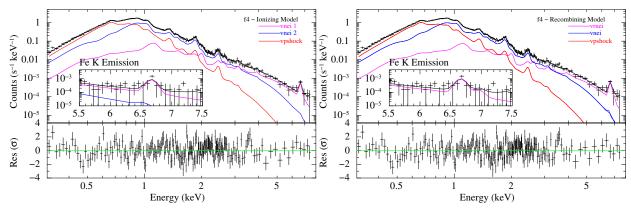
Figure C.10. Fits for blobs b1 and b2 protruding ahead of the western rim with the single vpshock model.

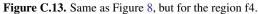


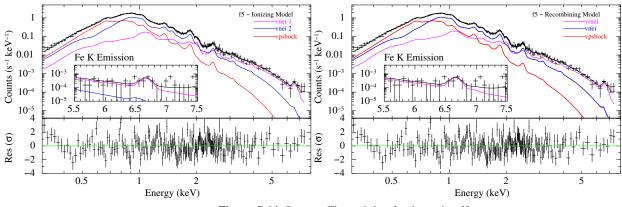














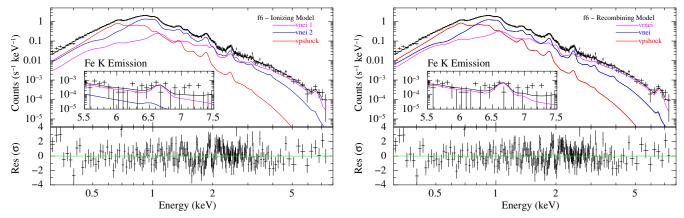


Figure C.15. Same as Figure 8, but for the region f6.

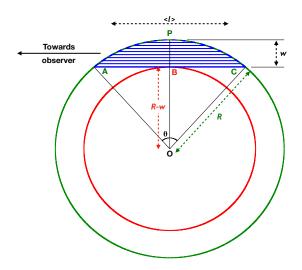


Figure D.1. Sketch of the geometry assumed for the calculation of the depth $\langle l \rangle$ of the regions used for spectral fitting along the rim. The blue shaded area, enclosed between the arc APC and the horizontal line AC, depicts the region along the line of sight, pictured in cross-section as part of a circular cylindrical shell defined by the green outer circle and the red inner circle. The opening angle $AOC \equiv \theta$ is determined by the width *w* and the distance of the region from the center of the remnant *R*. The shaded area is the difference between the pie-shaped region AOCPA and the triangle AOCBA.