1. Introduction

X-ray studies have revealed that many supernova remnants (SNRs) have recombining plasmas (RPs; e.g., Ozawa et al. 2009; Yamaguchi et al. 2009; Ohnishi et al. 2011; Uchida et al. 2012, 2015; Lopez et al. 2013a; Sato et al. 2014; Auchettl et al. 2015, 2017; Washino et al. 2016; Matsumura et al. 2017; Okon et al. 2018; Suzuki et al. 2018). In particular, their spectra show radiative recombination continua (RRCs) that arise when electrons collide and recombine with ions. RPs are overionized, where the electron temperature \( kT_e \) from the continuum is lower than the ionization temperature \( kT_i \) given by line ratios (Kawasaki et al. 2002, 2005), in contrast to a collisional ionization equilibrium (CIE) plasma where these temperatures are equal. Most young SNRs (with ages \( < 10^3 \) yr) are under-ionized, whereas older SNRs have reached CIE. However, in SNRs where rapid cooling has occurred, overionization is possible because the recombination age is longer than the cooling time (see the review by Yamaguchi 2020).

The origin of RPs is debated: the two proposed scenarios are rapid cooling arising from adiabatic expansion or from thermal conduction (the timescale for cooling via radiation is much too long; see Masai 1994 and Kawasaki et al. 2002). After gas is shock-heated to high temperatures, rapid cooling via adiabatic expansion occurs when the gas breaks through to a low-density interstellar medium (ISM; e.g., Moriya 2012; Shimizu et al. 2012). The electrons cool more rapidly than the ions, producing an overionized plasma (see, e.g., Itoh & Masai 1989; Yamaguchi et al. 2009). Thermal conduction, on the other hand, occurs when hot ejecta cool by the exchange of heat with cooler material (e.g., Cox et al. 1999; Shelton et al. 1999) that can have a short enough timescale to produce an overionized plasma (Kawasaki et al. 2002). Among the SNRs with evidence of RP, most show signs of interacting with molecular clouds (see Table 1 of Sun & Chen 2020 and references therein), indicating that this interaction is tied somehow to the rapidly cooling plasma. All SNRs with RPs are of the mixed-morphology class (Rho & Petre 1998), which tend to be mature SNRs with ages of \( \sim 4000–20,000 \) yr (see Section 10.3 of Vink 2012).

W49B (G43.3–0.2) is the youngest SNR with overionized plasma (\( \sim 2–6 \) kyr: Hwang et al. 2000; Zhou & Vink 2018; Sun & Chen 2020). Thus, W49B’s RP demonstrates that cooling can occur even in the early stages of SNR evolution. W49B is interacting with a molecular cloud on its eastern side (Keohane et al. 2007; Zhu et al. 2014), and it is expanding into a less dense ISM on its western side. Consequently, W49B is an ideal target to explore the origin of RPs and overionization in SNRs.

W49B was one of the first SNRs where signatures of a recombining/overionized plasma were discovered. Using integrated ASCA data, Kawasaki et al. (2005) measured the intensity ratios of He-like to H-like lines of Ar and Ca, and they found \( kT_e \sim 2.5 \) keV \( \gtrsim kT_i \sim 1.8 \) keV. They proposed that thermal conduction was the origin of the overionization and found that the thermal conduction timescale was less than the recombination age.

Subsequently, evidence of a recombining plasma in W49B was identified by Ozawa et al. (2009) using Suzaku observations: they found an RRC feature from He-like Fe at 8.830 keV and derived \( kT_e \sim 2.7 \) keV. Miceli et al. (2010) localized spatially the recombining plasma using XMM-Newton data by mapping the hardness ratio of the count rate in the 8.3–12 keV band to that in the 4.4–6.2 keV band. They found that the hardness ratio is enhanced in the center and west of W49B,
which these authors attributed to the Fe RRC. However, the limited counts in these XMM-Newton observations precluded a spatially resolved spectral modeling of these features, and the enhanced hardness ratio could have arisen from other emission mechanisms (e.g., bremsstrahlung, synchrotron) or from a high background.

Lopez et al. (2013b) presented a deep, 220 ks Chandra observation of W49B, and Lopez et al. (2013a) analyzed this data to measure $kT_e$ in 13 regions across the SNR using the He-like to H-like line ratios of S and Ar. They showed that the SNR is overionized in the west, where $kT_e < kT_0$, consistent with the adiabatic cooling scenario and the results of Miceli et al. (2010). Zhou & Vink (2018) performed a spatially resolved spectroscopic study using the Chandra data, and they found increased ionization timescale $\tau = n_e t$ and $kT_e$ in the west, with lower recombination ages of $\sim 2000$ yr there compared to that in the east ($\sim 6000$ yr).

Using Nuclear Spectroscopic Telescope Array (NuSTAR) observations, Yamaguchi et al. (2018) mapped the ratio of the Fe RRC line (at 8.8–10 keV) to the Fe He-$\alpha$ line (at 6.4–6.8 keV) in W49B. They found that this ratio is enhanced in the west, implying greater overionization there. In addition, Yamaguchi et al. (2018) conducted a spatially resolved spectral analysis of 12 regions across W49B, fitting data with a single RP model and linking the initial temperature $kT_{\text{init}}$ across the regions. The western regions exhibited lower $\tau$ and $kT_e$ than the eastern regions, again supporting the adiabatic cooling scenario.

Recently, Sun & Chen (2020) analyzed 2004 and 2014 XMM-Newton observations of W49B with a total effective exposure time of $\sim 230$ ks. They performed a global spectral analysis and showed that one CIE + two RP components fit the spectra well, with $kT_{\text{init}}$ values of $\sim 2.4$ and 4.5 keV. These results are consistent with the spatially resolved Chandra study of W49B performed by Zhou & Vink (2018), who found initial temperatures near $\sim 2.5$ keV in the east and $\gtrsim 5$ keV in the west. Sun & Chen (2020) suggested the high $kT_{\text{init}}$ component might have arisen from either thermal conduction or adiabatic cooling, whereas the lower $kT_{\text{init}}$ component likely originated from adiabatic cooling. Hydrodynamical simulations by Zhou et al. (2011) and Zhang et al. (2019) supported the possibility that both cooling scenarios together could explain the RP in W49B.

In this paper, we use the deep XMM-Newton observations of W49B to map the RP in order to ascertain the origin of the rapid cooling in the SNR. This work improves upon that of Sun & Chen (2020) by performing a spatially resolved analysis of the deep XMM-Newton data, and we make use of XSPEC’s RP models, which were unavailable at the time of Lopez et al. (2013a). The approach of the analysis is similar to Zhou & Vink (2018) and Yamaguchi et al. (2018), taking advantage of XMM-Newton’s better hard X-ray response than Chandra and improved spectral resolution relative to NuSTAR.

The paper is organized as follows. In Section 2, we present the observations as well as our methods of data reduction and spectral fitting. In Section 3, we describe the results and show maps of the best-fit parameters, discussing how they relate to the presence and origin of the overionized plasma in W49B. Finally, in Section 5, we summarize our findings and their implications.

## 2. Observations and Data Analysis

### 2.1. XMM-Newton Data Reduction

W49B has been observed using the XMM-Newton Observatory five times, with three observations in 2004 (ObsIDs 0084100401–0084100601; PI: Decourchelle) for 39.3 ks and two observations in 2014 (ObsIDs 0724270101 and 0724270201; PI: Lopez) for 189.7 ks. We only consider the recent pair of observations in order to limit the systematic effects from the instruments’ spectral response. These observations were taken on 2014 April 17–19, with both the MOS and PN detectors operated in the full-frame mode with the medium filter, and have exposure times of 118.5 ks and 71.2 ks, respectively. The SNR (with a diameter of $\sim 4'$; Green 2019) is fully enclosed by the field of view of the detectors.

To process the data, we used the XMM-Newton Science System (SAS) version 15.0.0 (Gabriel et al. 2004) and the most up-to-date calibration files to produce the data products for our analysis. As XMM-Newton suffers from both proton flares and a high background, we made count rate histograms using events with an energy between 10–12 keV and removed the time intervals that were contaminated by a high background or flares to produce our cleaned events. We found that these observations are only partially affected by high background/proton flares, giving an effective exposure time of 141.4 ks, 150.3 ks, and 90 ks for the MOS1, MOS2, and PN detectors, respectively. For all of the detectors, we used the standard screening procedures and screening set of FLAGS as suggested in the current SAS analysis threads and XMM-Newton Users Handbook. As W49B is located in the Galactic plane, it is possible that both Galactic Ridge X-ray emission and the Cosmic X-ray Background can contribute non-negligibly to the observed emission. To correct for this contamination, we used EVIGWEIGHT on all of the cleaned event files, which allows us to take vignetting into account. All analysis products and results presented below are from these cleaned, filtered, and vignetting-corrected event files.

We extracted spectra from 46 $0.5 \times 0.5'$ regions covering the spatial extent of the SNR (see Figure 1) using the SAS task EVSELECT. Spectral response and effective area files for each detector were produced using the SAS tasks ARFGEN and RMFGEN, respectively. Given the high signal from W49B, we accounted for the background using background subtraction from a $136'' \times 58''$ rectangular background region centered at $(\alpha, \delta) = (19 \text{ h}11\text{ m}18.1\text{ s}, +9\text{ d}11'26.7'')$. We combined the MOS1 and MOS2 spectra for each observation using the HEASARC command ADDASCASPEC.

### 2.2. Spectral Fitting

The spectral fitting was performed using the X-ray analysis software XSPEC Version 12.9.0 (Arnaud 1996) and ATOMDB Version 3.0.9 (Smith et al. 2001; Foster et al. 2012) over an energy range of 0.9–10.0 keV. Each spectrum was grouped with a minimum of 25 counts per energy bin using the FTOOLS command GRFPHA and fitted using $\chi^2$ statistics. We adopted solar abundances from Asplund et al. (2009).

We fit the spectra of each region using an absorbed model with one ISM component and two ejecta components. In every
region, we found that a single-ejecta component was insufficient to adequately fit the data (e.g., producing large residuals around prominent emission lines) and that it was necessary to include at least one RP component. We attempted using an underionized, overionized, or CIE model to describe the lower-temperature ejecta component, and we found that either an overionized or CIE component produced the best fit, depending on the region analyzed. We initially fit each region with two RP components, and if the ionization timescale exceeded $3 \times 10^{12}$ cm$^{-3}$ s, we fit the lower-temperature ejecta with a CIE component, since 90% of the material at temperatures of a few $10^5$ K reach CIE by a few $\times10^{12}$ cm$^{-3}$ s (Smith & Hughes 2010). In these cases, using a CIE model to fit the cooler ejecta resulted in a lower reduced $\chi^2$ than using a RP component.

Our final model for each region was either \texttt{phabs(xvapec+vvapec+vvnei)} or \texttt{phabs(xvapec+vvrnei+vvnei)}. The first \texttt{vvapec} component, a model for fitting a plasma in CIE with nonsolar abundances, represents the shock-heated ISM/CSM. For this component, we fixed Mg to 0.3 $Z_\odot$ to match the fits of Sun & Chen 2020, and other abundances were set to 1 $Z_\odot$. The middle \texttt{vvapec or vvnei} component represents the lower-temperature ejecta that either has reached CIE or is overionized, respectively. The final \texttt{vvnei} component represents the hot overionized ejecta. As a \texttt{vvnei} model reflects overionized plasma, in addition to the typical fitting parameters (e.g., current electron temperature $kT_e$, ionization timescale $\tau$, normalization norm, and abundances of various elements), the model also includes the parameter $kT_{\text{init}}$. This parameter captures the initial temperature of the plasma before rapid cooling occurred. In order to constrain the fits, we found it necessary to link $kT_{\text{init}}$ of the two RP ejecta components.

Additionally, we tied the abundances between the two ejecta components and allowed Mg, Si, S, Ar, Ca, Cr, Mn, Fe, and Ni to vary. Due to the high column density $N_{\text{H}}$ and a corresponding lack of line detections below $\sim1.1$ keV, we froze all elements lighter than Mg to solar metallicity. Generally, we found that the emission below $\sim1.9$ keV is largely produced by the ISM and cooler ejecta component and is attenuated by the high $N_{\text{H}}$ toward W49B. As such, we note that there may be a degeneracy between the fit parameters of these components (e.g., $N_{\text{H}}$, $kT_{\text{ISM}}$, $kT_{\text{e}}$, $\tau$, and the Si abundance). Above $\sim1.9$ keV, the hotter ejecta component dominates the flux, enabling more robust measurement of the associated parameters (e.g., $kT_{\text{e,2}}$, $kT_{\text{e,3}}$, and the S, Ar, and Ca abundances) to assess overionization.

Furthermore, in each ejecta component, we allow the redshift to vary in order to reflect the bulk motion. We note that most of the best-fit redshifts are $\sim$(2–4)$\times10^{-3}$ (see Table 2), corresponding to speeds of $\approx1000$ km s$^{-1}$ toward the observer.

### 2.2.1. Ionization Temperature and Fe RRC Measurements

Past studies of overionization in W49B (e.g., Kawasaki et al. 2005; Lopez et al. 2013a; Sun & Chen 2020) have calculated flux ratios between elements’ (Si, S, Ar, Ca) Ly$\alpha$ and He-$\alpha$ emission lines in order to estimate the ionization temperatures $kT_e$ of each element. These studies have shown that higher-mass elements have greater $kT_e$ (i.e., $kT_{e,\text{Ar}} \approx 2$ keV; $kT_{e,\text{Ca}} \approx 2.5$ keV) than lower-mass elements (i.e., $kT_{e,\text{S}} \approx 1$ keV; $kT_{e,\text{Si}} \approx 1.6$ keV) in W49B. Lopez et al. (2013a) concluded that the origin of these differences is unlikely to be physical, since heavier elements require longer ionization timescales to reach CIE (Smith & Hughes 2010). However, Sun & Chen (2020) suggested that the differences may arise because the Si and S are predominantly associated with the cooler RP, whereas the Ar and Ca are from the higher-temperature RP.

We examine the spatial distribution of $kT_e$ throughout the SNR to investigate the possible origin of these differing temperatures. To do this, we measure the continuum-subtracted fluxes of the Ly$\alpha$ and He-$\alpha$ lines for Si, S, Ar, and Ca. We account for the thermal continuum using the AtomDB NoLine model \texttt{APECNOLINE}, an XSPEC model that includes no emission lines. We adopt the best-fit values of our full spectral analysis (e.g., $N_{\text{H}}$, $kT_e$, norm, $\tau$) into a \texttt{phabs(apec+apec+apec)} model, where the 3 \texttt{apec} (noline) models represent the ISM, cool ejecta, and hot ejecta components. For each overionized ejecta component (\texttt{vvnei}), we subtract our derived \texttt{APECNOLINE} continuum to obtain the continuum-subtracted line flux of each element. We perform this calculation for the He-$\alpha$ and Ly$\alpha$ line of Si, S, Ar, and Ca. We then convert these flux ratios to $kT_e$ using the relations shown in Figure 6a of Sun & Chen (2020) and created from AtomDB data tables. We do not perform these calculations on the CIE ejecta, as all the flux ratios should correspond to temperatures equal to the electron temperature of the plasma.

We adopt the same approach as above to measure and map the flux of the Fe RRC line (at $E_{\text{edge}} = 8.83$ keV) as well (see Section 3.5 for more details).

### 3. Results

Table 2 in the Appendix lists the best-fit parameters for each of the 46 regions analyzed, including 1σ errors on all quantities that were derived using the XSPEC error command. Two example spectra and their best fits are presented in Figure 2. The left panel shows the best-fit spectra associated with region 17, where the cooler ejecta are found to be in CIE, while the right panel shows the spectra from region 23, where both ejecta components are overionized. In Sections 3.1–3.3, we consider

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http://www.atomdb.org/noline.php
the results associated with each spectral component and their implications.

3.1. N\textsubscript{H} and kT\textsubscript{ISM} Maps

In Figure 3, we show the best-fit N\textsubscript{H} and kT\textsubscript{ISM} maps. We find a range in best-fit N\textsubscript{H} of (7.2–8.5) \times 10\textsuperscript{22} cm\textsuperscript{-2} and best-fit kT\textsubscript{ISM} of 0.16–0.20 keV. These values are consistent with previous measurements by Lopez et al. (2013a), Zhou & Vink (2018), and Sun & Chen (2020).

N\textsubscript{H} is elevated in the center, east, and southwest, whereas it is comparatively lower in the southeast, northeast, and exterior of W49B. These results suggest that the dense material in front of (or associated with) the SNR is not uniform. We note that CO and warm H\textsubscript{2} have been detected in the east and southwest of W49B (Lacey et al. 2001; Keohane et al. 2007; Zhu et al. 2014), consistent with the enhanced N\textsubscript{H} in those directions. The elevated N\textsubscript{H} in region 11 (of N\textsubscript{H} = (8.76\textsuperscript{+0.05}/\textsuperscript{-0.07}) \times 10\textsuperscript{22} cm\textsuperscript{-2}) corresponds to a “hole” seen in Chandra images where X-rays below \sim 2.5 keV are attenuated (see Figure 3 of Lopez et al. 2013a) which suggests the existence of dense foreground material there.

Our kT\textsubscript{ISM} values are clustered around \approx 0.18 keV and are relatively constant across the SNR, varying only by \sim 20% in the 46 regions. We note that our kT\textsubscript{ISM} map tends to be anticorrelated with the best-fit N\textsubscript{H} (where regions of high N\textsubscript{H} have lower kT\textsubscript{ISM}). As discussed in Section 2.2, the N\textsubscript{H} and kT\textsubscript{ISM} are determined largely from the flux below \sim 2.5 keV, so it is possible that these components are partially degenerate with one another.

3.2. Cooler Ejecta Component Maps

In Figure 4, we show the maps of the parameters associated with the cooler ejecta component: the current electron temperature kT\textsubscript{e,1}, the initial temperature kT\textsubscript{init}, the ionization timescale \tau\textsubscript{i,1}, the recombination age t\textsubscript{rec,1}, and the ratio of kT\textsubscript{e,1}/kT\textsubscript{init}. We find a range in best-fit kT\textsubscript{e,1} of 0.31–0.76 keV and best-fit kT\textsubscript{init} of 2.72–4.26 keV. Our results are consistent with those of Sun & Chen (2020), who found kT\textsubscript{e,1} = 0.64 \pm 0.01 keV and kT\textsubscript{init} values of 2.42\textsuperscript{+0.06/\textsuperscript{-0.05} keV and 4.54\textsuperscript{+0.17/\textsuperscript{-0.15} keV of their cooler and hotter components, respectively, from the integrated XMM-Newton spectrum. Both of these temperature maps show enhanced temperatures along the bar, and kT\textsubscript{e,1} is additionally enhanced in the southeast.
The best-fit ionization timescales $\tau_1$ of the overionized cooler plasma are $\sim (7-14) \times 10^{11}$ cm$^{-3}$ s. We find that the cooler component has reached CIE in the east, as denoted by the white squares in the parameter maps in Figure 4. By contrast, the best-fit $\tau_1$ values in the west suggest that the cooler ejecta component has not reached CIE yet.

To examine the cooling across the SNR, we map $kT_{\text{init}}/kT_{e,1}$ in Figure 4. Enhanced ratios of $kT_{\text{init}}/kT_{e,1}$ may reflect more efficient initial cooling of electrons or a lower ionization timescale. As ionization timescale is $\tau = n_e t$, a lower ionization timescale can indicate lower-density medium and/or more recent cooling. We find the northwest has the highest ratios, and the south and central regions have comparatively lower $kT_{\text{init}}/kT_{e,1}$.

As stated in Section 2.2, we tied $kT_{\text{init}}$ of the cooler ejecta component to that of the hotter component. We note that the best-fit $kT_{\text{init}}$ and $\tau_1$ are correlated: greater $kT_{\text{init}}$ values correspond to greater $\tau_1$ values. This relationship arises since

Figure 4. Maps of the best-fit parameters of the lower-temperature (cooler) ejecta component with cyan contours overplotted from the broadband X-ray emission (from Chandra; Lopez et al. 2013a). The white squares in the maps reflect the plasma in CIE. The $t_{\text{rec}}$ is estimated by dividing $\tau_1$ by the estimated electron density $n_{e,1}$. The $\tau$-weighted $kT_{\text{init}}/kT_{e,1}$ map values are estimated by dividing the temperature ratio by the best-fit $\tau_1$ normalized to $10^{12}$ s cm$^{-3}$, as described in Section 3.2. North is up and east is left.
a higher temperature requires more time to reach the current ionization state. To correct for this degeneracy, we map an "effective $kT_{\text{init}}/kT_{\text{e,1}}$ ratio" defined as

$$\tau^{-}\text{weighted } \frac{kT_{\text{init}}}{kT_{\text{e,1}}} = \left( \frac{1 \times 10^{12} \text{ s cm}^{-3}}{\tau_1} \right) \times \left( \frac{kT_{\text{init}}}{kT_{\text{e,1}}} \right)$$

where we have divided the temperature ratio by the best-fit $\tau_1$ and normalized by $1 \times 10^{12} \text{ s cm}^{-3}$. In this context, the trend is even more pronounced; effective $kT_{\text{init}}/kT_{\text{e,1}}$ is greatest in the northwest and decreases in the east and south directions.

In Figure 4, we also present a map of the recombination age $t_{\text{rec},1}$. To compute $t_{\text{rec},1}$, we first estimate the electron density $n_e$ in each region across the SNR using the norm parameter of the cooler ejecta component, since $\text{norm} = (10^{-14}/4\pi D^2) \int n_H n_e dV$, where $D$ is the distance to the SNR, $n_H$ is the hydrogen number density, and $V$ is the volume of each region. We adopt a distance of $D = 9.3$ kpc, an intermediate value of the distance estimates of 8–11.3 kpc in the literature (e.g., Brogan & Troland 2001; Chen et al. 2014; Zhu et al. 2014; Ranasinghe & Leahy 2018). We assume that $n_e \approx 1.2 n_H$ as is the case for a fully ionized plasma with solar abundances. To calculate the volume of each region, we approximate each 0.5 x 0.5 region as a rectangular prism. We assume the SNR is spherical and estimate the depth $l$ of each region, where $l = 2 R^2/R - R^2$, $R$ is the radius of the SNR, and $r$ is the projected distance from the region to the SNR center. We adopt a radius $R = 2.37$, corresponding to 6.6 pc at $D = 9.3$ kpc, and a SNR center of R.A. $\alpha = 19^h11^m7.1^s$ and decl. $\delta = +9^\circ 6'14''04'$. Furthermore, we assume electron pressure equilibrium (i.e., $n_e n_H kT_{\text{e,1}} = n_e n_H kT_{\text{e,2}}$) in order to solve for the unknown filling factors of each plasma component. Finally, to calculate $t_{\text{rec},1}$, we divide the best-fit $\tau_1$ by the derived $n_e$. We note that since the environments of mixed-morphology SNRs like W49B tend to be quite clumpy (since of 3400 km s$^{-1}$), the current electron temperature $kT_{\text{e,1}}$ is greatest in the southwest, whereas the cooler ejecta had the most cooling in the northwest.

Our recombination age $t_{\text{rec},2}$ map for the hotter component has a similar east–west gradient as that of $t_{\text{rec},1}$: the central and western regions have $t_{\text{rec},2} \approx 500–1000$ yr, whereas the eastern side has $t_{\text{rec},2} \approx 1500–2500$ yr. Though these values are consistent with those of Zhou & Vink (2018), our $t_{\text{rec},2}$ range is less than the recombination age of 6000 +400 yr derived by Sun & Chen (2020) for their hotter RP. These disparate results likely arise from differences in the estimates of $n_e$: Sun & Chen (2020) found a hotter RP density of $\approx 2.1 \text{ cm}^{-3}$, whereas our $n_e$ range from $\approx 5–20 \text{ cm}^{-3}$.

Figure 6 shows the ratio of the hotter-to-cooler ejecta best-fit norm values, where norm$_{h}/\text{norm}_{c} > 1$ indicates that a region has greater emission measure in the hotter component. This map demonstrates that the hotter ejecta dominate eastern regions of W49B, the cooler ejecta dominates south-western regions, and the two are equally present in the north/northwest regions.

3.4. Ionization Temperatures

In Table 1, we summarize the range of ionization temperatures $kT_z$ obtained from our spectral modeling. Here we divide the findings into two categories: the cooler and the hotter overionized ejecta. For all regions, we find that higher-mass elements exhibit greater $kT_z$ than lower-mass elements, suggesting that the former are further out of CIE than the latter elements. This finding is consistent with the fact that lighter elements require shorter ionization timescales to reach CIE at temperatures $\geq 1 \text{ keV}$ (Smith & Hughes 2010). To determine the degree of overionization and to probe the physical origin of the recombining plasma, we compare $kT_z$ of each element to $kT_e$ in the ejecta components.

In Figure 7 we plot the ratio of the ionization temperature to the current electron temperature ($kT_{e,1}/kT_{e,1}$) and ($kT_{e,2}/kT_{e,2}$) for the Si, S, Ar, and Ca in both ejecta components. In the central and western regions, all of the elements in the cooler plasma have $kT_{e,1}/kT_{e,1} > 1$ (indicative of overionization) and show gradients of increasing $kT_{e,1}/kT_{e,1}$ from southeast to northwest. In the eastern regions with CIE plasma, each element’s ionization temperature is set to be equal to the electron temperature.

We note that the vast majority of the emission from S, Ar, and Ca is from the hotter ejecta component, whereas $\leq 60%$ of the total Si emission arises from the hotter ejecta component.
Figure 7 (right column) demonstrates this point by mapping the ratio of the flux in the He-α line of the hotter ejecta $F_{z,2}$ to the total He-α line flux of both ejecta components for each element ($F_{z,1} + F_{z,2}$). Given that the Ar and Ca contribute negligibly to the flux in the cooler RP in particular, the $kT_{Ar,1}/kT_{e,1}$ and $kT_{Ca,1}/kT_{e,1}$ maps have large uncertainties and should be interpreted with caution.

For the hotter RP ejecta component, all of the elements show a gradient of increasing $kT_{z,2}/kT_{e,2}$ toward the west/southwest, consistent with the $kT_{init}/kT_{e,2}$ map in Figure 5. In the western and central regions, all elements have $kT_{z,2}/kT_{e,2} > 1$. However, in the eastern regions, although the ratios of $kT_{z,2}/kT_{e,2} \geq 1$ for S, Ar, and Ca, we find that Si has $kT_{z,2}/kT_{e,2} < 1$, indicating that Si is underionized in the east. We note that the ~60% of Si emission in the eastern regions comes from the hotter ejecta component, indicating that this measurement is robust.

3.5. Fe RRC Map

The He-like Fe radiative recombination continuum (RRC) line at $E_{edge} = 8.83$ keV in W49B is a useful spectral feature to
hotter (with $kT_e = 0.87–1.62$ keV) ejecta components, based on the maps of $kT_{\text{min}}/kT_e$, $\tau$, $\tau_{\text{rec}}$ (Figures 4 and 5), $kT_{\text{rec}}/kT_e$ of each element (Figure 7), and the Fe RRC to He-$\alpha$ flux ratio (Figure 8). Given that W49B is impeded by molecular material to its east/southeast (Keohane et al. 2007; Lopez et al. 2013b; Zhu & Vink 2014), whereas it is now expanding into a lower-density ISM in the west, our results are consistent with the overionization predominantly arising from adiabatic expansion, as suggested in previous work (Miceli et al. 2010; Lopez et al. 2013a; Yamaguchi et al. 2018; Zhou & Vink 2018).

4.1. RP in Western and Central Regions

Although both ejecta components are generally more overionized in the west, the cooler RP is most strongly overionized in the northwest (Figure 4), and the bulk of the hotter RP overionization is found in the southwest (Figure 5). Both results are consistent with the adiabatic expansion scenario, as described above. However, it is possible that the southwest enhancement of overionization in the hot RP arises from interaction with CSM material there (Keohane et al. 2007; Chen et al. 2014) as the cold clouds mix with the shocked expanding plasma (Zhou et al. 2011), though the material may be in the foreground (Lacey et al. 2001). We note that a majority of the emission in the southwest of W49B (see Figure 6) arises from the cooler component, whereas the emission in the northwest is produced equally by the hot and cool RPs. Taken together with the maps of Figures 4 and 5, we see that the bulk of the overionized ejecta are toward the west/northwest, farthest away from the eastern molecular cloud and consistent with rapid cooling from adiabatic expansion.

For these central and western regions, the $kT_{z}/kT_e$ maps for Si, S, Ar, and Ca show increasing ionization temperatures for higher-mass elements (see Figure 7). This increasing ionization temperature is similar to that found in past studies (Kawasaki et al. 2005; Lopez et al. 2013a; Sun & Chen 2020), consistent with the fact that heavier elements require a factor of a few higher ionization timescales to reach CIE at temperatures of $\gtrsim 1$ keV (Smith & Hughes 2010). These ionization temperatures are higher in the western regions of W49B, supporting the existence of more highly ionized plasma there. As each element’s ionization temperature map shows a similar distribution, we conclude that the different ionization temperatures between Si/S and Ar/Ca do not arise because of associations with distinct RP components.

4.2. RP in Eastern Regions

We find that the cooler ejecta in the east of W49B, where the SNR is impeded by molecular material, are best fit with a CIE component. This finding is consistent with the results of Zhou & Vink (2018), who found that their single-ejecta component is in CIE to the east. In order for these eastern regions to be in equilibrium when the western regions are not, either the ionization timescales must be greater or there must have been less rapid cooling of electrons. The former can result from longer elapsed time since the cooling, enabling the ions to reach equilibrium, or from a higher-density ambient medium. The latter scenario could be due to less effective cooling or to the east never being overionized.

We are unable to constrain $\tau_{\text{rec},1}$ in these regions, but we note that our best-fit ambient density in the cooler eastern ejecta

| Element | Cooler RP | Hotter RP |
|---------|-----------|-----------|
| Si      | 0.7–0.9   | 1.1–1.3   |
| S       | 1.0–1.4   | 1.6–1.8   |
| Ar      | 1.9–2.4   | 2.2–2.4   |
| Ca      | 2.4–2.7   | 2.7–3.0   |

Figure 6. Map of the best-fit norm$_2$/norm$_1$, the ratio of the normalizations of the hotter and cooler ejecta components, with cyan contours overplotted from the broadband X-ray emission (from Chandra; Lopez et al. 2013a). Larger ratios correspond to greater flux from the hotter RP component. North is up and east is left.
Figure 7. Maps of the ionization temperature to electron temperature ratios \( (kT_z/kT_e) \) for Si, S, Ar, and Ca for both the cooler (left column) and hotter ejecta components (middle column). The \( kT_z/kT_e \) color maps have the same scale for easier visual comparison. The right column shows the fractional flux of the He-\( \alpha \) line of each element in the hot ejecta component (e.g., \( F_{Si,1} \)) relative to the total from both ejecta components (e.g., \( F_{Si,1} + F_{Si,2} \)). North is up and east is left.
and east is left.

\( \text{n}_{e,1} \approx 10 \text{ cm}^{-3} \) is higher than that of the hotter ejecta \( \text{n}_{e,1} \approx 30 \text{ cm}^{-3} \). This could support the theory that the cooler ejecta could have once been overionized but the ejecta cooled faster. We also note that the majority of the flux in the east of W49B is from the hotter RP (see Figure 6), suggesting that the majority of ejecta in the east are hotter and still overionized.

Given the close proximity between the two ejecta, it is likely that the cooler ejecta were also once overionized.

In contrast to Lopez et al. (2013a) and Zhou & Vink (2018), we find evidence of overionization in the hotter ejecta in the east of W49B where the SNR is impacting molecular material, though the amount of overionization is \( \approx 1.5-2 \times \) less than in the west. These differences suggest that the regions closest to the molecular cloud in the east did not cool as rapidly as the freely expanding regions in the west/northwest and the less dense regions in the southwest. This reduced cooling may result from the lack of low-density medium to expand into or because cooling via thermal conduction is not as efficient as cooling from adiabatic expansion.

4.3. Thermal Conduction Timescales

As discussed above, we find greater overionization in the west of W49B, but overionized ejecta are present in the east as well. In these regions, the hotter ejecta are overionized, while the cooler ejecta are in CIE. While the western regions’ cooling is likely a result of adiabatic expansion, the overionization in the eastern regions could be a result of adiabatic expansion and/or thermal conduction. It is possible that the cooler ejecta were once overionized but have reached equilibrium, or may have never been overionized.

To examine the origin of the rapid cooling in the east, we calculate the thermal conduction timescale \( t_{\text{cond}} \) using

\[
 t_{\text{cond}} \approx 634 \left( \frac{\text{n}_e}{1 \text{ cm}^{-3}} \right) \left( \frac{\ell_T}{1 \text{ pc}} \right)^2 \left( \frac{kT_e}{1.0 \text{ keV}} \right)^{-5/2} \left( \frac{\ln \Lambda}{32} \right) \text{yr} \tag{1}
\]

where \( \text{n}_e \) is the average electron density, \( \ell_T \) is the scale length of the temperature gradient, \( \ln \Lambda \) is the Coulomb logarithm, and \( kT_e \) is the electron temperature. Although most past studies use the current electron temperature \( kT_e \) (e.g., Kawasaki et al. 2002; Zhou et al. 2014; Uchida et al. 2012) to calculate \( t_{\text{cond}} \), a few others use the initial electron temperature \( kT_{\text{init}} \) (e.g., Sun & Chen 2020). We note that the actual \( t_{\text{cond}} \) should fall between the values calculated by using these two temperatures, given that the electron conductivity will slow as the temperature drops and electrons become less mobile. Thus, we perform the analysis using \( kT_{\text{init}} \) as a lower limit and \( kT_e \) as an upper limit for \( t_{\text{cond}} \). However, we note that the true timescale is likely closer to that calculated using \( kT_{\text{init}} \) as the high temperature would allow for rapid (and thus the majority of the) cooling.

Using Equation (1), we estimate \( t_{\text{cond}} \) for the eastern regions for both ejecta components. For the hotter overionized ejecta, we compare \( t_{\text{cond,2}} \) to the recombination age \( t_{\text{rec,2}} \). If \( t_{\text{cond,2}} \lesssim t_{\text{rec,2}} \), then it is plausible that thermal conduction is the origin of the hotter RP. Otherwise, thermal conduction could not cool the electrons faster than the ions recombined, and an alternate cooling mechanism (e.g., adiabatic expansion) is necessary. For the cooler ejecta in CIE, we compare \( t_{\text{cond,1}} \) to the SNR age \( t_{\text{SNR}} \). If \( t_{\text{cond,1}} < t_{\text{SNR}} \), then it is possible that the cooler ejecta were once overionized but have since cooled via thermal conduction. Otherwise, the cooler ejecta either underwent rapid cooling by a different mechanism or were never significantly overionized.

In the eastern regions, we find \( \text{n}_{e,2} \approx 10 \text{ cm}^{-3} \) for the hotter ejecta and \( \text{n}_{e,1} \approx 30 \text{ cm}^{-3} \) for the cooler ejecta (as calculated in Section 3.2). We assume \( \ell_T = 3 \text{ pc} \) \((\sim 1.1)\) to match the distance from the CIE boundary to the unshocked, cool ISM east of the SNR. Using the average initial electron temperatures of \( kT_{\text{init}} \approx 4.5 \text{ keV} \) (recall that we tied the initial temperatures between the two RP components), we find \( t_{\text{cond,1}} \approx 4 \text{ kyr} \) for the cooler ejecta and \( t_{\text{cond,2}} \approx 1.3 \text{ kyr} \) for the hotter ejecta. However, we note that our assumption that the two RPs have the same \( kT_{\text{init}} \) likely yields an upper limit for \( t_{\text{cond}} \) of the cooler component. For reference, Sun & Chen (2020) found that \( t_{\text{cond,1}} \approx 2.4 \text{ keV} \), which would result in \( t_{\text{cond,1}} \approx 19 \text{ kyr} \). Thus, \( t_{\text{cond,1}} \) calculated using the initial temperatures is likely somewhere between 4 and 19 kyr.

If we use the current electron temperatures, \( kT_{e,1} \approx 0.6 \text{ keV} \) and \( kT_{e,2} \approx 1.6 \text{ keV} \), we find that \( t_{\text{cond,1}} = 613 \text{ kyr} \) for the cooler RP and \( t_{\text{cond,2}} = 17.6 \text{ kyr} \) for the hotter RP. Combined, our allowed ranges are 4–19 kyr \( \lesssim t_{\text{cond,1}} \lesssim 613 \text{ kyr} \) and 1.3 kyr \( \lesssim t_{\text{cond,2}} \lesssim 17.6 \text{ kyr} \), where we note that the lower values are more likely. As \( t_{\text{rec,2}} \approx 1500–3000 \text{ yr} \), it is possible that large-scale thermal conduction can explain the overionization of the hotter ejecta. However, the calculated values for \( t_{\text{cond,1}} \) are equal or greater than \( t_{\text{SNR}} \) of \( \sim 2–6 \text{ kyr} \), indicating that cooling via thermal conduction is not a plausible origin of overionization in the cooler ejecta.

4.3.1. Small-scale Thermal Conduction

As noted in the introduction, models (Zhou et al. 2011; Zhang et al. 2019) find that thermal conduction is necessary to reproduce the observed morphology (specifically the bar) of W49B. These works split thermal conduction into large- and small-scale processes, claiming that large-scale thermal conduction smoothed the temperature and density distributions, whereas the small-scale thermal conduction led to cloud evaporation (see Cowie et al. 1981 and White & Long 1991) that produced a thermal X-ray emitting core and overionization features. We note that past studies (Vink 2012; Zhou et al. 2014; Sun & Chen 2020) have set \( \ell_T \approx \ell_{\text{SNR}} \), the radius of the SNR, thereby calculating the timescale for large-scale thermal conduction.
To investigate the timescale for small-scale thermal conduction, we compute the thermal conduction timescales using \( t_T \approx 1 \) pc (a value between the lower limit and average cloud size from McKee & Ostriker 1977). We note that (Zhou et al. 2011; Zhang et al. 2019) use saturated thermal conduction in their models, which occurs when length scales are less than the electron mean free path \( \lambda_{\text{mfp}} \), whereas our Equation (1) is for classical conduction. However, we calculate \( \lambda_{\text{mfp}} \lesssim 0.1 \) pc throughout our regions which is less than the expected minimum cloud size of \( \sim 0.4 \) pc (McKee & Ostriker 1977).

Thus, we can continue to use the equation for classical thermal conduction. For the cooler ejecta, using these scale length results in 440 yr \( \lesssim t_{\text{cond},1} < 70 \) kyr. If instead we adopt \( k T_{\text{init},1} \approx 2.4 \) keV (as found by Sun & Chen 2020), we find an alternate lower limit of 2 kyr for \( t_{\text{cond},1} \). For the hotter ejecta, these \( t_T \) result in 140 yr \( \leq t_{\text{cond},2} < 2 \) kyr.

Using these length scales, we find that \( t_{\text{cond},2} \) is generally \( \lesssim t_{\text{rec},2} \), indicating that rapid cooling via small-scale thermal conduction is a plausible origin for the hotter RP. For the cooler plasma, we find that only the lower range of \( t_{\text{cond},1} \) is less than \( t_{\text{SNR}} \), and \( t_{\text{cond},1} \) approaches \( t_{\text{SNR}} \) if we use \( k T_{\text{init},1} \approx 2.4 \) keV.

Thus, in order for thermal conduction to have caused significant overionization in the cooler ejecta, then clouds of sizes \( < 1 \) pc are preferred.

### 5. Conclusions

We performed a spatially resolved study using deep XMM-Newton observations of W49B to investigate the presence, location, and physical origin of overionized plasma within the SNR. To that end, we modeled the spectra of 46 \( 0.5 \times 0.5 \) regions in W49B. We make use of the high signal to fit the data with a three-component model: one ISM component plus two ejecta components. To investigate the degree of overionization, we produced temperature, \( \tau \), and \( t_{\text{rec}} \) maps for each ejecta component as well as ionization temperature to current temperature maps for Si, S, Ar, and Ca.

We find that W49B contains overionized plasma across the entire SNR, present in a gradient of increasing overionization from east to west. Our results are broadly consistent with past studies of recombing plasma in W49B (e.g., Miceli et al. 2010; Lopez et al. 2013a; Yamaguchi et al. 2018; Zhou & Vink 2018; Sun & Chen 2020). Given that the western regions furthest from the eastern molecular cloud interaction (Keohane et al. 2007; Zhu et al. 2014) show the greatest overionization (with \( k T_{\text{rec}} / k T_e \approx 4 \)), we attribute the origin of the majority of recombing plasma in W49B to rapid cooling from adiabatic expansion of shock-heated plasma into a lower-density ISM. In contrast with the results of Lopez et al. (2013a) and Zhou & Vink (2018), we find significant overionization (\( k T_{\text{init}} / k T_e \approx 2 \)) in the eastern regions of the SNR as well, mainly from the hotter ejecta.

For the hotter ejecta, it is possible that large-scale thermal conduction is the origin of overionization, based on our finding that \( t_{\text{cond},2} < t_{\text{rec},2} \) using a temperature of \( k T_{\text{init}} \approx 4.5 \) keV. However, it is unlikely that large-scale thermal conduction could have produced overionization in the cooler ejecta, given our result that \( t_{\text{cond},1} > t_{\text{SNR}} \).

Additionally, we find that small-scale thermal conduction resulting in cloud evaporation of \( \lesssim 1 \) pc-sized clouds can cool both plasmas in short enough times. For the hotter ejecta, average cloud sizes of \( \sim 1.6 \) pc produce \( t_{\text{cond},2} \lesssim t_{\text{rec},2} \). For the cooler ejecta, cloud sizes of \( < 1 \) pc are necessary to produce overionization on a timescale \( \lesssim t_{\text{SNR}} \). We conclude that it is possible that the cooler ejecta was once overionized via small-scale thermal conduction, but it remains possible that these cooler ejecta were never overionized.

Lastly, we note that it is important to consider which temperature to use in Equation (1). \( k T_{\text{init}} \) produces a better estimate of \( t_{\text{cond}} \) than \( k T_e \), as cooling is most rapid when temperature, and thus conductivity, is high. By adopting \( k T_e \), the timescales increase significantly and do not reflect the past temperature changes of the plasma.

Our spatially resolved spectral analysis of W49B, combined with the previous studies of W49B’s abundances, recombing plasma, and morphology (e.g., Kawasaki et al. 2005; Lopez et al. 2009, 2013a, 2013b; Ozawa et al. 2009; Yang et al. 2009; Miceli et al. 2010; Zhu et al. 2014; Yamaguchi et al. 2018; Sun & Chen 2020) can be used to inform future simulations investigating the progenitor, explosion processes, and recombination physics required to create this SNR. For example, simulations by Zhou et al. (2011), Zhang et al. (2019) investigate the recombination physics and ISM structure required to produce W49B’s morphology assuming a spherically symmetric explosion and concluded that small-scale thermal conduction via cloud evaporation is necessary to reproduce its features. Our observational study confirms that small-scale thermal conduction is a viable origin for RP in the east of W49B regardless of whether the explosion was symmetric or asymmetric.

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**Software:** XMM-Newton SAS (v15.0.0; Gabriel et al. 2004), XSPEC (v12.9.0; Arnaud 1996), ATOMDB v3.0.9; Smith et al. 2001; Foster et al. 2012, ftools (Blackburn 1995).

### Appendix

Table 2 in this Appendix lists the best-fit parameters for each of the 46 regions analyzed, including 1-\( \sigma \) errors on all quantities that were derived using the XSPEC `error` command.
## Table 2
Best-fit Model Parameters

| Parameter | Region 1 | Region 2 | Region 3 | Region 4 | Region 5 | Region 6 | Region 7 | Region 8 | Region 9 | Region 10 |
|-----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|
| $N_1$ ($10^{22}$ cm$^{-2}$) | 7.57 ± 0.04 | 7.51 ± 0.06 | 7.595 ± 0.04 | 7.46 ± 0.04 | 7.62 ± 0.03 | 7.86 ± 0.04 | 7.67 ± 0.06 | 7.33 ± 0.02 | 8.11 ± 0.05 | 8.10 ± 0.02 |
| ISM vapec$^a$ component | | | | | | | | | | |
| $kT_{\text{ISM}}$ (keV) | 0.154 ± 0.003 | 0.173 ± 0.003 | 0.187 ± 0.002 | 0.211 ± 0.007 | 0.1983 ± 0.001 | 0.1746 ± 0.001 | 0.178 ± 0.001 | 0.188 ± 0.006 | 0.177 ± 0.001 | 0.182 ± 0.001 |
| Redshift$^b$ (10$^{-3}$) | 3.12 | -0.72 | -3.14 | -3.33 | 3.38 | -5.43 | -3.65 | 4.03 | -0.24 | -2.99 |
| Norm$^c$ (cm$^{-5}$) | 1.81 | 0.77 | 1.94 | 1.13 | 2.81 | 8.45 | 4.76 | 1.75 | 2.33 | 4.66 |

Ejecta 1 vapec or vvrnle$^c$ component

| $kT_{\text{v}}$ (keV) | 0.45 ± 0.03 | 0.31 ± 0.02 | 0.47 ± 0.03 | 0.54 ± 0.03 | 0.62 ± 0.02 | 1.63 ± 0.06 | 0.51 ± 0.01 | 0.51 ± 0.01 | 0.51 ± 0.01 | 0.44 ± 0.02 | 0.40 ± 0.00 | 0.53 ± 0.03 |
| $\gamma_1$ (10$^{11}$ cm$^{-3}$ s) | ... | ... | 10.3 ± 0.6 | 8.80 ± 0.5 | 6.49 ± 0.21 | 8.35 ± 0.17 | 6.57 ± 0.29 | 5.42 ± 0.40 | 5.15 ± 0.72 | 3.57 ± 0.53 | 8.43 ± 0.70 | 6.80 ± 0.21 |
| Redshift$^d$ (10$^{-3}$) | -2.48 | -2.35 | -0.09 | 0.05 | -4.27 | 0.25 | -0.07 | -3.35 | -4.17 | -2.68 |
| Norm (10$^{-3}$ cm$^{-5}$) | 3.91 ± 0.34 | 0.99 ± 0.63 | 3.40 ± 0.31 | 3.67 ± 0.45 | 3.65 ± 0.29 | 8.71 ± 0.17 | 6.12 ± 0.31 | 3.01 ± 0.43 | 5.08 ± 0.66 | 4.69 ± 0.37 |

Ejecta 2 vvrnle$^c$ component

| $kT_{\text{v}}$ (keV) | 1.64 ± 0.02 | 1.47 ± 0.02 | 1.48 ± 0.03 | 1.32 ± 0.02 | 1.28 ± 0.03 | 1.13 ± 0.07 | 1.07 ± 0.08 | 1.01 ± 0.02 | 1.59 ± 0.02 | 1.66 ± 0.01 |
| $\gamma_2$ (10$^{11}$ cm$^{-3}$ s) | 0.07 ± 0.19 | 4.05 ± 0.14 | 3.07 ± 0.08 | 3.72 ± 0.16 | 4.19 ± 0.18 | 3.86 ± 0.03 | 4.06 ± 0.21 | 4.06 ± 0.42 | 4.43 ± 0.28 | 3.86 ± 0.05 |
| Si | <1.85 | <2.33 | 5.18 ± 0.37 | 6.51 ± 0.90 | 4.83 ± 0.24 | 4.83 ± 0.06 | 5.15 ± 0.72 | 8.43 ± 0.70 | 6.80 ± 0.21 |
| S | 6.67 ± 0.19 | 11.7 ± 0.3 | 9.18 ± 0.29 | 9.80 ± 0.66 | 9.66 ± 0.40 | 11.7 ± 0.4 | 11.8 ± 0.4 | 12.0 ± 1.1 | 13.3 ± 0.3 | 9.8 ± 0.2 |
| Ar | 11.4 ± 0.5 | 19.3 ± 0.8 | 14.7 ± 0.5 | 16.5 ± 0.5 | 15.6 ± 0.4 | 17.8 ± 0.5 | 20.4 ± 0.5 | 18.8 ± 0.7 | 19.5 ± 0.6 | 14.7 ± 0.5 |
| Mg | 8.36 ± 0.18 | 14.7 ± 0.5 | 12.4 ± 0.3 | 14.1 ± 0.7 | 13.3 ± 0.4 | 15.1 ± 0.7 | 16.9 ± 0.7 | 17.1 ± 1.1 | 17.4 ± 0.2 | 13.0 ± 0.2 |
| Cr | 19.2 ± 0.8 | 31.1 ± 1.4 | 18.6 ± 0.2 | 28.8 ± 0.24 | 27.9 ± 0.29 | 25.2 ± 2.3 | 22.2 ± 3.5 | 30.1 ± 5.4 | 32.5 ± 2.4 | 15.1 ± 1.9 |
| Mn | 59.7 ± 6.9 | 77.8 ± 1.4 | 52.7 ± 0.9 | 55.7 ± 0.40 | 48.8 ± 0.28 | 46.3 ± 0.31 | 39.5 ± 2.6 | 39.8 ± 2.4 | 38.6 ± 2.0 | 32.8 ± 2.3 |
| Ni | 16.4 ± 0.5 | 35.5 ± 0.7 | 20.8 ± 0.6 | 19.0 ± 0.1 | 14.9 ± 0.4 | 14.2 ± 0.7 | 13.8 ± 0.3 | 12.7 ± 1.1 | 29.0 ± 0.3 | 20.7 ± 0.3 |
| Fe | 29.0 ± 3.8 | 86.0 ± 12.9 | 42.8 ± 3.6 | 44.2 ± 4.7 | 15.5 ± 1.4 | 14.1 ± 4.4 | 10.8 ± 5.1 | <5.16 | 6.81 ± 2.8 | 29.4 ± 2.3 |
| Norm (10$^{-3}$ cm$^{-5}$) | 5.98 ± 0.23 | 4.85 ± 0.27 | 3.89 ± 0.08 | 3.396 ± 0.33 | 3.596 ± 0.09 | 3.096 ± 0.08 | 3.0 ± 0.08 | 3.13 ± 0.21 | 5.53 ± 0.54 | 4.17 ± 0.28 |
| $\gamma_2$ (10$^{11}$ cm$^{-3}$ s) | 3.90 ± 0.47 | 4.05 ± 0.54 | 3.89 ± 0.08 | 3.396 ± 0.33 | 3.596 ± 0.09 | 3.096 ± 0.08 | 3.0 ± 0.08 | 3.13 ± 0.21 | 5.53 ± 0.54 | 4.17 ± 0.28 |

| $\chi^2$/dof | 1.09 | 1.12 | 1.08 | 1.06 | 1.11 | 1.21 | 1.14 | 1.15 | 1.12 | 1.17 |
Table 2
(Continued)

| Parameter                  | Region 11          | Region 12          | Region 13          | Region 14          | Region 15          | Region 16          | Region 17          | Region 18          | Region 19          | Region 20          |
|---------------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| $N_H$ ($10^{22}$ cm$^{-2}$) |
|                           | 8.76 ± 0.03        | 7.92 ± 0.02        | 8.11 ± 0.03        | 8.01 ± 0.01        | 7.65 ± 0.03        | 7.27 ± 0.01        | 7.90 ± 0.06        | 8.00 ± 0.02        | 8.10 ± 0.02        | 8.07 ± 0.01        |
| ISM vapec component       |
| $kT_e$ (keV)              | 0.17 ± 0.00        | 0.176 ± 0.00       | 0.173 ± 0.00       | 0.178 ± 0.00       | 0.181 ± 0.00       | 0.195 ± 0.00       | 0.170 ± 0.00       | 0.179 ± 0.00       | 0.174 ± 0.00       | 0.176 ± 0.00       |
| Redshift (10$^{-3}$)      | 0.03               | 0.02               | 0.03               | 0.02               | 0.02               | 0.02               | 0.02               | 0.01               | 0.01               | 0.02               |
| Norm (cm$^{-5}$)          | 262               | 10.4               | 15.41              | 9.86               | 4.19               | 1.37               | 4.71               | 6.88               | 12.31              | 12.66              |
| Ejecta 1 vvape or vvnei component^d |
| $kT_e$ (keV)              | 0.60 ± 0.01        | 0.55 ± 0.01        | 0.51 ± 0.01        | 0.52 ± 0.01        | 0.50 ± 0.01        | 0.42 ± 0.01        | 0.45 ± 0.03        | 0.54 ± 0.01        | 0.51 ± 0.05        | 0.53 ± 0.02        |
| $\tau_1$ (10$^{11}$ cm$^{-3}$ s) | 7.31 ± 0.01        | 7.39 ± 0.11        | 7.47 ± 0.10        | 6.86 ± 0.02        | 6.52 ± 0.01        | 6.08 ± 0.19        | 6.08 ± 0.34        | 14.16 ± 0.54       | 7.78 ± 0.06        | 7.81 ± 0.15        |
| $\tau_2$ (10$^{13}$ cm$^{-5}$) | 8.40 ± 0.15        | 8.49 ± 0.19        | 10.6 ± 0.2         | 10.2 ± 0.5         | 9.44 ± 0.26        | 3.59 ± 0.05        | 4.23 ± 0.76        | 4.30 ± 0.58        | 9.05 ± 0.14        | 11.1 ± 0.1        |
| Norm (10$^{-3}$ cm$^{-5}$) | 8.06 ± 0.15        | 8.49 ± 0.19        | 10.6 ± 0.2         | 10.2 ± 0.5         | 9.44 ± 0.26        | 3.59 ± 0.05        | 4.23 ± 0.76        | 4.30 ± 0.58        | 9.05 ± 0.14        | 11.1 ± 0.1        |
| Ejecta 2 vvnei component^d |
| $kT_e$ (keV)              | 1.88 ± 0.02        | 1.62 ± 0.02        | 1.40 ± 0.01        | 1.17 ± 0.01        | 1.08 ± 0.01        | 0.94 ± 0.01        | 1.53 ± 0.03        | 1.61 ± 0.01        | 1.59 ± 0.05        | 1.58 ± 0.01        |
| $kT_{\text{m}n}$ (keV)    | 4.26 ± 0.08        | 3.96 ± 0.03        | 4.18 ± 0.03        | 3.94 ± 0.11        | 3.97 ± 0.09        | 4.07 ± 0.12        | 4.54 ± 0.31        | 4.08 ± 0.10        | 4.00 ± 0.04        | 3.92 ± 0.02        |
| Mg                         | 9.57 ± 0.54        | 4.06 ± 0.44        | 2.90 ± 0.37        | 3.62 ± 0.44        | 3.64 ± 0.28        | 4.93 ± 0.02        | 6.22 ± 0.95        | 9.07 ± 0.72        | 3.77 ± 0.31        | 4.24 ± 0.62        |
| Si                         | 11.4 ± 0.2         | 9.19 ± 0.16        | 9.09 ± 0.11        | 11.4 ± 0.2         | 9.78 ± 0.20        | 11.1 ± 0.5         | 12.8 ± 0.2         | 13.3 ± 0.2         | 9.64 ± 0.12        | 10.57 ± 0.2        |
| Ar                         | 14.2 ± 0.2         | 12.4 ± 0.12        | 11.5 ± 0.1         | 15.7 ± 0.2         | 14.3 ± 0.05        | 16.0 ± 0.2         | 15.7 ± 0.3         | 16.2 ± 0.2         | 12.1 ± 0.1         | 13.8 ± 0.1        |
| Ca                         | 14.5 ± 0.3         | 13.9 ± 0.3         | 12.3 ± 0.3         | 17.8 ± 0.4         | 17.0 ± 0.4         | 17.4 ± 0.6         | 16.5 ± 0.6         | 17.2 ± 0.4         | 13.9 ± 0.3         | 15.4 ± 0.2        |
| Cr                         | 16.7 ± 0.3         | 16.3 ± 0.3         | 12.4 ± 0.3         | 17.8 ± 0.4         | 18.0 ± 0.4         | 17.8 ± 0.6         | 17.3 ± 0.5         | 17.6 ± 0.3         | 14.0 ± 0.2         | 15.6 ± 0.2        |
| Mn                         | 13.8 ± 1.1         | 19.4 ± 1.4         | 22.2 ± 1.8         | 30.0 ± 2.5         | 20.7 ± 2.6         | 29.3 ± 3.8         | 30.9 ± 3.0         | 21.7 ± 2.0         | 16.5 ± 1.3         | 23.0 ± 1.5        |
| Fe                         | 21.3 ± 3.2         | 30.5 ± 3.6         | 34.3 ± 3.6         | 39.5 ± 3.8         | 26.7 ± 3.8         | 98.5 ± 34.5        | 50.3 ± 6.8         | 38.3 ± 4.4         | 26.6 ± 3.8         | 30.9 ± 3.1        |
| Ni                         | 17.4 ± 0.7         | 18.2 ± 0.1         | 16.3 ± 0.1         | 15.3 ± 0.2         | 11.6 ± 0.6         | 13.1 ± 0.6         | 24.5 ± 0.8         | 25.7 ± 0.3         | 18.8 ± 0.7         | 20.6 ± 0.4        |
| $\tau_2$ (10$^{11}$ cm$^{-3}$ s) | 21.0 ± 1.9         | 38.8 ± 2.1         | 31.4 ± 2.9         | 28.8 ± 3.0         | 15.1 ± 3.3         | <3.67             | 62.6 ± 5.3         | 61.4 ± 2.1         | 39.7 ± 1.8         | 46.0 ± 2.9        |
| Redshift (10$^{-3}$)      | −2.05              | −1.94              | −2.81              | 2.82               | −3.17              | −2.11             | −3.22             | −3.30              | −3.22              | −1.94             |
| Norm (10$^{-3}$ cm$^{-5}$) | 6.57               | 8.71               | 10.02              | 8.27               | 6.44               | 3.04              | 3.88              | 6.39               | 10.94              | 9.62              |
| $\chi^2$/dof              | 1.18               | 1.25               | 1.19               | 1.19               | 1.12               | 1.12              | 1.17              | 1.24               | 1.29               | 1.29              |
### Table 2  
(Continued)

| Parameter | Region 21 | Region 22 | Region 23 | Region 24 | Region 25 | Region 26 | Region 27 | Region 28 | Region 29 | Region 30 |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $N_H$ ($10^{22}$ cm$^{-2}$) | 8.04 ±0.01 | 8.03 ±0.01 | 7.77 ±0.04 | 7.51 ±0.09 | 7.74 ±0.02 | 7.83 ±0.03 | 7.75 ±0.03 | 8.30 ±0.08 | 8.08 ±0.04 | 7.97 ±0.03 |
| ISM vapec$^a$ component | | | | | | | | | | |
| $kT_e$ (keV) | 0.173 ±0.001 | 0.178 ±0.001 | 0.190 ±0.001 | 0.181 ±0.002 | 0.173 ±0.001 | 0.174 ±0.001 | 0.177 ±0.002 | 0.166 ±0.003 | 0.178 ±0.001 | 0.183 ±0.001 |
| Redshift$^b$ ($10^{-3}$) | −5.57 | −2.73 | 3.91 | 6.54 | 5.10 | 3.70 | 3.18 | 5.74 | 0.13 | 0.01 |
| Norm$^c$ (cm$^{-3}$) | 12.29 | 8.41 | 3.30 | 2.65 | 5.03 | 8.15 | 6.02 | 12.63 | 7.41 | 4.87 |
| Ejecta 1 vapec or vvrnel$^c$ component | | | | | | | | | | |
| $kT_e$ (keV) | 0.51 ±0.01 | 0.51 ±0.01 | 0.46 ±0.01 | 0.39 ±0.03 | 0.55 ±0.02 | 0.54 ±0.01 | 0.55 ±0.03 | 0.45 ±0.01 | 0.56 ±0.01 | 0.57 ±0.01 |
| $\tau_1$ (10$^{11}$ cm$^{-5}$ s) | 9.45 ±0.21 | 6.76 ±0.09 | 7.06 ±0.10 | 8.05 ±0.67 | ... | ... | ... | 10.57 ±0.18 | 6.84 ±0.11 | 5.50 ±0.06 |
| Redshift$^d$ ($10^{-3}$) | 0.14 | −4.26 | −4.24 | 2.77 | −5.24 | −2.47 | −2.53 | −0.07 | −4.31 | −4.31 |
| Norm (10$^{-3}$ cm$^{-5}$) | 8.04 ±0.11 | 8.94 ±0.15 | 8.09 ±0.41 | 4.57 ±0.90 | 2.98 ±0.20 | 5.15 ±0.47 | 5.19 ±0.35 | 10.63 ±0.25 | 11.57 ±0.04 | 10.83 ±0.07 |
| Ejecta 2 vvrnel$^c$ component | | | | | | | | | | |
| $kT_e$ (keV) | 1.29 ±0.01 | 1.21 ±0.01 | 1.04 ±0.01 | 0.37 ±0.04 | 1.50 ±0.02 | 1.52 ±0.01 | 1.45 ±0.01 | 1.36 ±0.02 | 1.33 ±0.03 | 1.36 ±0.01 |
| $kT_{mea}$ (keV) | 3.74 ±0.02 | 3.619 ±0.017 | 3.562 ±0.085 | 3.81 ±0.045 | 4.69 ±0.026 | 4.59 ±0.07 | 4.26 ±0.15 | 4.01 ±0.04 | 3.78 ±0.11 | 3.84 ±0.04 |
| Mg | 6.06 ±0.13 | 5.16 ±0.07 | 3.67 ±0.35 | 5.86 ±0.98 | 8.78 ±0.12 | 10.2 ±0.6 | 5.46 ±0.09 | 5.90 ±0.62 | 2.55 ±0.31 | 3.65 ±0.37 |
| Si | 13.1 ±0.30 | 12.0 ±0.2 | 12.1 ±0.2 | 12.5 ±0.6 | 11.7 ±0.1 | 13.8 ±0.2 | 11.5 ±0.16 | 11.5 ±0.7 | 8.14 ±0.18 | 8.74 ±0.01 |
| S | 16.6 ±0.31 | 16.7 ±0.2 | 17.4 ±0.2 | 17.3 ±0.7 | 13.3 ±0.2 | 15.6 ±0.2 | 13.9 ±0.14 | 13.7 ±0.6 | 11.4 ±0.4 | 12.6 ±0.5 |
| Ar | 18.2 ±0.34 | 18.0 ±0.2 | 19.8 ±0.4 | 19.8 ±1.0 | 13.7 ±0.2 | 16.9 ±0.4 | 15.9 ±0.7 | 15.3 ±0.3 | 11.9 ±0.3 | 13.8 ±0.4 |
| Ca | 18.9 ±0.34 | 18.5 ±0.4 | 18.9 ±0.5 | 18.9 ±1.0 | 14.8 ±0.5 | 17.9 ±0.5 | 15.6 ±0.35 | 16.0 ±0.35 | 12.4 ±0.3 | 13.5 ±0.3 |
| Cr | 33.2 ±2.53 | 35.2 ±1.3 | 43.9 ±2.8 | 50.3 ±3.12 | 25.3 ±2.6 | 28.0 ±3.1 | 21.1 ±2.1 | 21.2 ±2.9 | 15.8 ±2.2 | 23.7 ±2.9 |
| Mn | 60.9 ±4.88 | 51.3 ±0.9 | 49.1 ±1.4 | 47.7 ±1.65 | 50.2 ±7.4 | 53.4 ±5.9 | 32.3 ±3.4 | 22.9 ±6.8 | 33.0 ±4.9 | 23.4 ±3.3 |
| Fe | 25.1 ±0.42 | 16.0 ±0.2 | 12.8 ±0.2 | 13.0 ±1.0 | 18.6 ±1.05 | 24.8 ±2.0 | 20.9 ±0.4 | 18.3 ±0.2 | 12.5 ±0.2 | 9.5 ±0.14 |
| Ni | 58.0 ±3.57 | 28.2 ±0.1 | 14.4 ±1.2 | <3.37 | 49.6 ±4.0 | 76.8 ±2.2 | 62.7 ±2.8 | 42.5 ±4.9 | 33.2 ±7.7 | 12.3 ±4.1 |
| $\tau_2$ (10$^{11}$ cm$^{-5}$ s) | 3.13 ±0.03 | 2.53 ±0.09 | 2.84 ±0.04 | 4.02 ±0.32 | 6.43 ±0.56 | 6.34 ±0.10 | 5.35 ±0.21 | 4.27 ±0.07 | 4.27 ±0.07 | 3.17 ±0.11 |
| Redshift$^e$ ($10^{-3}$) | −2.81 | −2.81 | −2.82 | −2.35 | −3.22 | −3.24 | −3.24 | −2.02 | −1.94 | |
| Norm$^f$ (10$^{-3}$ cm$^{-5}$) | 7.64 | 5.96 | 4.84 | 3.53 | 4.00 | 5.96 | 6.14 | 6.10 | 5.43 | 4.05 |
| $\chi^2$/dof | 1.24 | 1.16 | 1.19 | 1.09 | 1.14 | 1.19 | 1.24 | 1.22 | 1.10 | 1.10 |
| Parameter                  | Region 31 | Region 32 | Region 33 | Region 34 | Region 35 | Region 36 | Region 37 | Region 38 | Region 39 | Region 40 |
|---------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $N_H$ ($10^{22}$ cm$^{-2}$) | 7.76–0.07 | 7.19–0.06 | 7.38–0.03 | 7.27–0.06 | 7.50–0.07 | 7.68–0.07 | 8.15–0.08 | 8.06–0.05 | 7.48–0.12 | 7.18–0.02 |

**ISM vapen component**

| $kT_e$ (keV) | 0.175–0.002 | 0.177–0.002 | 0.1906–0.001 | 0.189–0.002 | 0.189–0.002 | 0.189–0.003 | 0.177–0.002 | 0.174–0.002 | 0.178–0.003 | 0.195–0.005 |
|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Redshift$^b$ (10$^{-3}$) | 6.72 | 5.52 | –5.66 | 2.56 | –0.72 | –5.32 | –4.94 | 6.89 | 6.64 | –0.74 |
| Norm$^c$ (cm$^{-3}$) | 4.97 | 2.32 | 2.84 | 1.87 | 1.83 | 1.93 | 4.78 | 4.40 | 1.92 | 1.21 |

**Ejecta 1 vapen or vvnen component**

| $kT_e$ (keV) | 0.48–0.02 | 0.47–0.02 | 0.76–0.01 | 0.60–0.01 | 0.57–0.02 | 0.43–0.03 | 0.47–0.02 | 0.49–0.03 | 0.46–0.03 | 0.74–0.02 |
|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $\tau_1$ (10$^{11}$ cm$^{-3}$ s) | 8.06–0.66 | 8.57–0.26 | … | … | … | 10.2–0.54 | 8.11–0.44 | 7.66–0.27 | 8.42–0.58 | … |
| Redshift$^b$ (10$^{-3}$) | 0.15 | 0.16 | –1.94 | –2.12 | –2.13 | –0.64 | –1.34 | 0.06 | –0.14 | –2.47 |
| Norm$^c$ (10$^{-3}$ cm$^{-5}$) | 6.83–0.56 | 5.73–0.37 | 3.91–0.10 | 5.59–0.55 | 3.34–0.34 | 9.06–1.00 | 9.90–0.79 | 5.06–0.72 | 3.55–0.41 | 2.04–0.05 |

**Ejecta 2 vvnen component**

| $kT_e$ (keV) | 0.972–0.032 | 0.900–0.021 | 1.53–0.016 | 1.39–0.024 | 1.90–0.007 | 1.00–0.003 | 1.05–0.002 | 1.07–0.003 | 0.99–0.005 | 0.90–0.004 | 1.54–0.008 |
|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $kT_{\text{mea}}$ (keV) | 3.25–0.04 | 3.38–0.09 | 4.06–0.08 | 4.42–0.08 | 3.61–0.10 | 3.32–0.32 | 3.54–0.20 | 3.38–0.21 | 3.58–0.25 | 4.09–0.09 | 3.85–0.19 |
| Mg | 2.85–0.71 | 3.28–0.35 | 7.04–0.38 | 5.62–0.36 | 5.78–0.44 | 4.15–0.45 | 3.94–0.38 | 5.15–0.98 | 5.04–0.93 | 6.53–0.46 |
| Si | 11.3–0.7 | 10.3–0.6 | 8.91–0.20 | 9.36–0.15 | 12.1–0.6 | 9.86–0.26 | 8.21–0.64 | 12.0–0.9 | 14.1–1.2 | 9.61–0.18 |
| S | 15.9–0.7 | 15.7–0.6 | 12.0–0.2 | 12.2–0.0 | 15.5–0.6 | 13.4–0.4 | 11.5–0.9 | 17.2–0.6 | 21.5–1.0 | 12.9–0.3 |
| Ar | 18.6–0.7 | 19.4–1.1 | 13.8–0.4 | 15.4–0.3 | 18.2–0.6 | 16.2–1.5 | 13.3–1.2 | 20.0–1.3 | 25.4–2.3 | 15.1–1.5 |
| Ca | 18.2–0.7 | 17.5–0.9 | 13.6–0.4 | 14.9–0.4 | 15.6–0.6 | 16.8–0.7 | 14.3–1.4 | 19.5–1.6 | 24.9–2.5 | 13.9–2.4 |
| Cr | 30.8–4.1 | 27.4–6.1 | 18.7–2.1 | 22.7–2.6 | 33.4–6.0 | 17.8–4.3 | 14.1–3.6 | 61.7–17.6 | 88.0–37.8 | 14.7–2.6 |
| Mn | >150 | 49.3–15.1 | 39.5–4.9 | 36.5–5.3 | 35.4–14.7 | 29.5–14.2 | 27.2–11.2 | 46.7–14.1 | 40.8–18.1 | 27.8–3.4 |
| Fe | 11.5–0.7 | 9.83–0.42 | 14.5–0.2 | 16.2–0.4 | 14.0–0.7 | 11.2–1.1 | 7.88–0.92 | 11.8–1.3 | 13.5–1.8 | 14.9–0.7 |
| Ni | 10.8–0.8 | <4.75 | 29.4–1.8 | 50.6 | 3.0 | 36.4–12.4 | 41.1–1.63 | <7.42 | 19.4–1.8 | 17.5–1.3 |
| $\tau_2$ (10$^{11}$ cm$^{-3}$ s) | 2.39–0.25 | 2.41–0.29 | 4.19–0.09 | 4.35–0.18 | 2.89–0.19 | 2.46–0.42 | 2.33–0.28 | 2.44–0.32 | 2.46–0.37 | 3.73–0.26 |
| Redshift$^b$ (10$^{-3}$) | –2.15 | –2.30 | –3.20 | –3.20 | –2.82 | –3.16 | –3.33 | –2.41 | –2.38 | –2.81 |
| Norm$^c$ (10$^{-3}$ cm$^{-5}$) | 5.69 | 3.84 | 5.75 | 5.92 | 4.03 | 3.62 | 4.13 | 3.43 | 2.72 | 2.98 |
| $\chi^2$/dof | 1.11 | 1.13 | 1.17 | 1.18 | 1.13 | 1.12 | 1.11 | 1.06 | 1.05 | 1.10 |
| Parameter | Region 41 | Region 42 | Region 43 | Region 44 | Region 45 | Region 46 |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $N_{\text{H}}$ ($10^{22}$ cm$^{-2}$) | $7.36_{-0.01}^{+0.03}$ | $7.07_{-0.02}^{+0.03}$ | $7.13_{-0.03}^{+0.03}$ | $7.47_{-0.10}^{+0.04}$ | $7.83_{-0.08}^{+0.03}$ | $7.42_{-0.12}^{+0.17}$ |
| ISM $\text{vvapec}$ component | | | | | | |
| $kT_e$ (keV) | $0.188_{-0.001}^{+0.001}$ | $0.191_{-0.002}^{+0.002}$ | $0.188_{-0.002}^{+0.001}$ | $0.185_{-0.001}^{+0.001}$ | $0.177_{-0.002}^{+0.001}$ | $0.177_{-0.002}^{+0.001}$ |
| Redshift<sup>b</sup> ($10^{-5}$) | $-0.73$ | $-0.74$ | $0.22$ | $7.06$ | $7.52$ | $-4.80$ |
| Norm<sup>b</sup> (cm$^{-5}$) | $2.38$ | $1.13$ | $1.17$ | $1.41$ | $1.93$ | $0.77$ |
| Ejecta 1 $\text{vvapecor vvnei}$ component | | | | | | |
| $kT_e$ (keV) | $0.73_{-0.02}^{+0.01}$ | $0.52_{-0.02}^{+0.03}$ | $0.54_{-0.02}^{+0.02}$ | $0.56_{-0.02}^{+0.04}$ | $0.49_{-0.02}^{+0.03}$ | $0.43_{-0.02}^{+0.02}$ |
| $\tau_{1}$ ($10^{11}$ cm$^{-3}$ s) | $14.44_{-0.32}^{+0.43}$ | $12.22_{-0.41}^{+0.37}$ | $9.18_{-0.40}^{+0.18}$ | $8.03_{-0.50}^{+0.18}$ | $7.40_{-0.13}^{+0.34}$ | $7.40_{-0.13}^{+0.34}$ |
| Redshift<sup>b</sup> ($10^{-5}$) | $-1.92$ | $-3.03$ | $-2.12$ | $-2.66$ | $-1.92$ | $0.14$ |
| Norm<sup>b</sup> ($10^{-5}$ cm$^{-5}$) | $3.03_{-0.04}^{+0.07}$ | $7.70_{-0.20}^{+0.31}$ | $6.54_{-0.18}^{+0.26}$ | $4.53_{-0.77}^{+0.27}$ | $5.34_{-0.27}^{+0.17}$ | $4.71_{-0.50}^{+0.21}$ |
| Ejecta 2 $\text{vvnei}$ component | | | | | | |
| $kT_e$ (keV) | $1.44_{-0.01}^{+0.01}$ | $1.02_{-0.01}^{+0.01}$ | $0.92_{-0.03}^{+0.03}$ | $1.00_{-0.04}^{+0.04}$ | $0.96_{-0.02}^{+0.04}$ | $0.97_{-0.04}^{+0.03}$ |
| $kT_{\text{init}}$ (keV) | $3.84_{-0.04}^{+0.08}$ | $3.87_{-0.09}^{+0.16}$ | $3.73_{-0.06}^{+0.07}$ | $2.95_{-0.26}^{+0.18}$ | $2.72_{-0.15}^{+0.20}$ | $3.28_{-0.12}^{+0.12}$ |
| Mg | $6.11_{-0.43}^{+0.49}$ | $2.58_{-0.28}^{+0.23}$ | $1.86_{-0.23}^{+0.24}$ | $3.41_{-0.44}^{+0.49}$ | $2.81_{-0.50}^{+0.54}$ | $2.50_{-0.38}^{+0.38}$ |
| Si | $11.2_{-0.2}^{+0.2}$ | $6.0_{-0.13}^{+0.16}$ | $4.47_{-0.14}^{+0.13}$ | $5.98_{-0.70}^{+0.65}$ | $7.25_{-0.32}^{+0.24}$ | $7.70_{-0.44}^{+0.36}$ |
| S | $14.7_{-0.3}^{+0.2}$ | $8.00_{-0.11}^{+0.17}$ | $6.28_{-0.13}^{+0.16}$ | $8.50_{-0.65}^{+0.29}$ | $10.7_{-0.28}^{+0.32}$ | $12.2_{-0.38}^{+0.24}$ |
| Ar | $17.4_{-0.4}^{+0.6}$ | $9.58_{-0.39}^{+0.39}$ | $7.04_{-0.36}^{+0.36}$ | $9.89_{-0.69}^{+0.69}$ | $12.3_{-1.6}^{+1.6}$ | $13.8_{-2.3}^{+2.3}$ |
| Ca | $14.9_{-0.4}^{+0.5}$ | $9.39_{-0.44}^{+0.45}$ | $7.51_{-0.39}^{+0.39}$ | $11.1_{-0.68}^{+0.71}$ | $15.1_{-1.8}^{+1.8}$ | $15.9_{-1.0}^{+1.0}$ |
| Cr | $15.3_{-0.2}^{+0.2}$ | $14.2_{-0.3}^{+0.7}$ | $12.6_{-3.4}^{+3.4}$ | $25.2_{-6.1}^{+6.1}$ | $37.8_{-7.9}^{+7.9}$ | $33.5_{-8.5}^{+8.5}$ |
| Mn | $22.2_{-3.7}^{+3.8}$ | <8.82 | <8.20 | 18.8_{-13}^{+4} | 32.7_{-13}^{+7} | <22.9 |
| Fe | $15.7_{-0.2}^{+0.2}$ | $7.53_{-0.21}^{+0.21}$ | $5.44_{-0.65}^{+0.65}$ | $7.74_{-1.21}^{+1.21}$ | $8.00_{-0.30}^{+0.30}$ | $8.49_{-0.49}^{+0.47}$ |
| Ni | $28.8_{-2.6}^{+2.4}$ | <3.34 | <2.47 | <3.56 | <5.74 | <16.5 |
| $\tau_{2}$ (cm$^{-3}$ s) | $2.84_{-0.13}^{+0.10}$ | $3.04_{-0.13}^{+0.23}$ | $2.88_{-0.08}^{+0.10}$ | $2.12_{-0.18}^{+0.21}$ | $1.40_{-0.39}^{+0.20}$ | $2.23_{-0.39}^{+0.20}$ |
| Redshift<sup>b</sup> ($10^{-5}$) | $-2.81$ | $-2.90$ | $-3.33$ | $-2.81$ | $-2.80$ | $-2.79$ |
| Norm<sup>b</sup> ($10^{-5}$ cm$^{-5}$) | $3.48$ | $3.94$ | $4.13$ | $2.36$ | $2.14$ | $1.79$ |
| $\chi^2$/dof | $1.18$ | $1.10$ | $1.13$ | $1.15$ | $1.14$ | $1.02$ |

Notes.

<sup>a</sup> All abundances frozen to 1, except for Mg which was frozen to 0.3 to match the analysis of (Sun & Chen 2020).

<sup>b</sup> Frozen after initial fit to better constrain the other parameters.

<sup>c</sup> $kT_{\text{init}}$ tied to the initial temperature of the 2nd ejecta component.

<sup>d</sup> Element abundances linked to the Ejecta 2 abundances.

<sup>e</sup> Unspecified abundances frozen to 1.

<sup>f</sup> Unconstrained and thus frozen after initial fit.
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