Forbidden Line Emission from Type Ia Supernova Remnants Containing Balmer-dominated Shells

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Abstract

Balmer-dominated shells in supernova remnants (SNRs) are produced by collisionless shocks advancing into a partially neutral medium and are most frequently associated with Type Ia supernovae. We have analyzed Hubble Space Telescope (HST) images and Very Large Telescope (VLT)/Multi-Unit Spectroscopic Explorer (MUSE) or AAT/Wide Field Integral Spectrograph observations of five Type Ia SNRs containing Balmer-dominated shells in the LMC: 0509−67.5, 0519−69.0, N103B, DEM L71, and 0548−70.4. Contrary to expectations, we find bright forbidden-line emission from small dense knots embedded in four of these SNRs. The electron densities in some knots are higher than $10^4$ cm$^{-3}$. The size and density of these knots are not characteristic for interstellar medium—they most likely originate from a circumstellar medium ejected by the SN progenitor. Physical property variations of dense knots in the SNRs appear to reflect an evolutionary effect. The recombination timescales for high densities are short, and HST images of N103B taken 3.5 yr apart already show brightness changes in some knots. VLT/MUSE observations detect [Fe XIV] line emission from reverse shocks into SN ejecta as well as forward shocks into the dense knots. Faint [O III] line emission is also detected from the Balmer shell in 0519−69.0, N103B, and DEM L71. We exclude the postshock origin because the [O III] line is narrow. For the preshock origin, we considered three possibilities: photoionization precursor, cosmic-ray precursor, and neutral precursor. We conclude that the [O III] emission arises from oxygen that has been photoionized by [He II] $\lambda$304 photons and is then collisionally excited in a shock precursor heated mainly by cosmic rays.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Supernova remnants (1667); Type Ia supernovae (1728); Large Magellanic Cloud (903); Shocks (2086)

1. Introduction

Supernova remnants (SNRs) are commonly identified by diffuse X-ray emission, nonthermal radio emission, and high [S II]/Hα ratio, which are characteristics produced by high-velocity shocks. However, some SNRs exhibit optical spectra that are dominated by hydrogen Balmer lines with no or very weak forbidden lines. Such “Balmer-dominated” spectra were first observed in the Tycho SNR (Kirshner & Chevalier 1978) and subsequently detected in SN 1006 (Schweizer & Lasker 1978), Kepler SNR (Fesen et al. 1989), RCW 86 (Long & Blair 1990), and Cygnus Loop (Raymond et al. 1983) in the Galaxy, and 0509−67.5, 0519−69.0, DEM L71 (0505−67.9), 0548−70.4 (Tuohy et al. 1982), and N103B (0509−68.7) (Williams et al. 2014; Li et al. 2017) in the Large Magellanic Cloud (LMC).

Of the above SNRs, only the Cygnus Loop originates from a core-collapse supernova. Its SNR shock velocities are low and [O III] and [O II] forbidden lines are seen where the shocked gas cools. The spectra of the Cygnus Loop’s Balmer filaments have been modeled by a ~400 km s$^{-1}$ nonradiative shock (Medina et al. 2014). The other SNRs containing Balmer-dominated shells are all of Type Ia and are young or relatively young. The weakness or absence of forbidden lines and the observed narrow core and broad wings of their Balmer-line profiles (Smith et al. 1991) can be explained by collisionless shocks advancing into a partially neutral medium (Chevalier et al. 1980). The interstellar neutral H atoms enter the shock front and can be collisionally excited and emit Balmer lines, forming the narrow core, while the postshock thermalized interstellar protons can go through charge exchange with the neutrals and emit Balmer lines, forming broad wings (Heng 2010).

For some of the Type Ia SNRs with Balmer-dominated shells/filaments, forbidden-line emission is detected at a significant level. In the cases of Kepler (Blair et al. 1991; Sankrit et al. 2008) and N103B (Li et al. 2017), bright forbidden lines are detected from dense knots that represent a circumstellar medium (CSM) ejected by the progenitor before the SN explosion, indicating that the progenitor white dwarf must have accreted material from a normal star companion.

Faint forbidden lines associated with the forward and reverse shocks in Type Ia SNRs with Balmer-dominated shells have also been reported. For example, [O I] $\lambda$6300 line emission associated with the Balmer shell has been reported in N103B and suggested to be excited in the cosmic-ray precursors of the Balmer-dominated forward shocks (Ghavamian et al. 2017). For SNRs with a dense CSM component, such as N103B, the forward radiative or partially radiative shocks into the CSM at shock speeds of 350−450 km s$^{-1}$ can excite coronal [Fe XIV] $\lambda$5303 and other coronal lines, as seen in N103B (Ghavamian et al. 2017). Similarly, reverse shocks driven into the SN ejecta at 350−450 km s$^{-1}$ speed can also excite coronal [Fe XIV] line.
emission, as reported in SNRs 0509–67.5, 0519–69.0, and N103B (Seitenzahl et al. 2019). In the two largest Type Ia SNRs with Balmer-dominated shells, DEM L71 and 0548–70.4, the presence of isolated patches of [O III] λ5007 emission has been interpreted as an indication of the SNR shocks becoming radiative (Tuohy et al. 1982).

In a program to search for surviving companions of Type Ia SN progenitors in the LMC (Li et al. 2017, 2019; Litke et al. 2017), we have studied Hubble Space Telescope (HST) Hα images of the Type Ia SNRs with Balmer-dominated shells 0509–67.5, 0519–69.0, N103B, DEM L71, and 0548–70.4, as shown in Figure 1. Unexpectedly, we find numerous nebular knots in DEM L71, similar to those seen in N103B and Kepler. We have also used archival integral field unit type observations of these five Type Ia SNRs to extract continuum-subtracted line images. These superb imaging and spectroscopic data make it possible to discover faint forbidden-line emission and resolve dense knots.

This paper reports our search and analysis of forbidden-line emission from five Type Ia SNRs with Balmer-dominated shells in the LMC. Section 2 describes the data used in this work, Section 3 introduces the method of our analysis, Section 4 reports results of individual SNRs, and Section 5 discusses the implication of the forbidden-line emission on the nature of the SN progenitors and the SNR shocks. Section 6 summarizes this study.

2. Observations

2.1. Hubble Space Telescope Observations

We have obtained new HST Hα images of SNR N103B, DEM L71, and SNR 0548–70.4, using the UVIS channel of Wide Field Camera 3 (WFC3) with the F656N filter in Program 13282 (PI: Chu). The UVIS channel of WFC3 has a 162″ × 162″ field of view and a 0″04 pixel size. The observations were dithered with the WFC3-UVIS-GAP-LINE pattern for 3 points and point spacings of 2″414. The total exposure time for each SNR is 1350 s.

Archival HST Hα images of SNRs 0509–67.5 and 0519–69.0 taken with the Advanced Camera for Surveys (ACS) and the F658N filter are available in the Hubble Legacy Archive. In addition, archival HST WFC3 Hα, [O III], and [S II] images of N103B are also available.

The HST imaging observations we use are listed in Table 1, where the filter, PI, program ID, date of observation, and exposure time are given.

2.2. VLT MUSE Observations

We have used archival Multi-Unit Spectroscopic Explorer (MUSE) observations obtained with the Very Large Telescope (VLT) UT4 for SNRs 0509–67.5, 0519–69.0, N103B, and DEM L71. MUSE is an integral field unit (IFU), which provides a spectrum for every position in the field of view (FOV). For these observations, the FOV is 60″ × 60″, large enough to encompass the entire SNR shell for the three small objects, but not DEM L71. The wavelength coverage, 4750–9350 Å, includes nebular lines such as Hα, Hβ, [O III] λλ4959, 5007, [N II] λλ6548, 6583, and [S II] λλ6716, 6731. The spatial and spectral samplings are 0″2 spaxel−1 and 1.25 Å pixel−1, respectively. The archival MUSE observations are listed in Table 1 with PI, program ID, date of observation, and exposure time information.

Figure 1. Hα images of the five LMC Type Ia SNRs with Balmer-dominated shells: 0509–67.5, 0519–69.0, N103B, DEM L71, and 0548–70.4 (from top to bottom). Images in the left panels were obtained with the MOSAIC II camera on the Blanco 4 m Telescope at Cerro Tololo Inter-American Observatory and images in the right panels were taken with the Hubble Space Telescope. The field of view of each panel is 3′ × 3′ with north at the top and east to the left.
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| Telescope | Instrument | SNR | Filter | PI | Program ID | Date | $t_{exp}$ (s) |
|-----------|------------|-----|--------|----|------------|------|-------------|
| HST       | ACS/WFC   | 0509-67.5 | F658N | Hughes | 11015 | 2006 Oct 28 | 4620 |
| HST       | WFPC2     | 0509-67.5 | F656N | Hughes | 11015 | 2007 Nov 7 | 14300 |
| HST       | ACS/WFC   | 0509-67.5 | F658N | Hovey | 14733 | 2016 Nov 13 | 10662 |
| HST       | ACS/WFC   | 0519-69.0 | F658N | Hughes | 12017 | 2011 Apr 21 | 4757 |
| HST       | WFC3/UVIS | N103B   | F656N | Chu   | 13282 | 2013 Jul 11 | 1350 |
| HST       | WFC3/UVIS | N103B   | F502N | Williams | 14359 | 2017 Jan 3 | 2051 |
| HST       | WFC3/UVIS | N103B   | F657N | Williams | 14359 | 2017 Jan 3 | 2979 |
| HST       | WFC3/UVIS | N103B   | F673N | Williams | 14359 | 2017 Jan 3 | 1982 |
| HST       | WFC3/UVIS | DEM L71 | F656N | Chu   | 13282 | 2014 Mar 5 | 1350 |
| HST       | WFC3/UVIS | 0548-70.4 | F656N | Chu   | 13282 | 2013 Sep 20 | 1350 |
| VLT       | MUSE      | 0509-67.5 | ...   | Morlino | 0100.D-0151 | 2018 Jan 22 | 701 |
| VLT       | MUSE      | 0519-69.0 | ...   | Leibundgut | 096.D-0352 | 2016 Jan 17 | 900 |
| VLT       | MUSE      | N103B   | ...   | Leibundgut | 096.D-0352 | 2015 Dec 12 | 900 |
| VLT       | MUSE      | DEM L71 | ...   | Leibundgut | 096.D-0352 | 2015 Nov 16 | 900 |
| ATT       | WiFeS     | 0548-70.4 | ...   | Seitenzahl | 4150178 | 2015 Dec 14 | 1800 |

We follow the standard procedure and use the VLT MUSE data reduction pipeline (Weilbacher et al. 2014) to carry out bias subtraction, flat-fielding, and wavelength and geometrical calibrations.

2.3. ATT WiFeS Observations

We have used the Wide Field Integral Spectrograph (WiFeS) observations obtained with the Advanced Technology Telescope (ATT) for SNR 0548–70.4.

The FOV of ATT WiFeS is $25'' \times 38''$, much smaller than the extent of SNR 0548–70.4. Thus, observations for a grid of $3 \times 5$ fields were planned to map the entire SNR, as shown in Figure 2; however, due to the weather condition, only four fields were observed. Among these observed fields, only fields G4 and G9 have adequate quality and contain forbidden-line emission to be presented in this study.

The ATT WiFeS is a double-beam spectrograph that simultaneously covers the blue and red wavelength ranges. For SNR 0548–70.4, the B3000 and R7000 gratings were used for the blue (3500–5700 Å) and the red (5400–7024 Å) wavelength ranges, respectively. The overall wavelength coverage is thus 3500–7024 Å, which includes all major nebular lines in the optical. The spatial sampling is $1''0 \times 1''5$ spaxel$^{-1}$, while the spectral samplings are 0.768 Å pixel$^{-1}$ for the blue spectral range and 0.439 Å pixel$^{-1}$ for the red spectral range. The ATT WiFeS observation of SNR 0548–70.4 is listed in Table 1 with pertinent information, such as PI, program ID, date of observation, and exposure time.

3. Method of Analysis

We start our analysis with a general examination of the HST H$\alpha$ images of the five Type Ia SNRs with Balmer-dominated shells in the LMC. HST images allow us to resolve nebular features as small as 0''05, i.e., 0.0125 pc in the LMC. We have learned from our previous study of the SNR N103B that HST H$\alpha$ images resolve two major types of morphological features: Balmer-dominated long filaments that delineate a shell structure, and forbidden-line-emitting dense knots that are distributed in groups in the SNR interior or along some Balmer filaments (Li et al. 2017). Thus, we first use the HST H$\alpha$ images to examine the shell structure and to search for dense nebular knots.

We then extract nebular line images from the VLT MUSE and ATT WiFeS data to search for nebular features that emit forbidden lines. These IFU data cubes allow us to extract images in wavelength intervals that cover nebular lines as well as images in adjacent line-free wavelength intervals. A clean line image can be obtained by subtracting the latter from the former. Line images extracted in this way are more sensitive than ground-based images taken with filters because sky lines and continuum background, especially the stars, are both removed. It is thus not surprising that we indeed have detected faint emission features that were not seen before.

A large number of forbidden lines of low-ionization species, such as [N II], [O I], [O III], [S II], [Ca II], and [Ni II], are detected in the dense knots (Ghavamian et al. 2017; Dopita et al. 2019) and forbidden lines of high-ionization species, such as [Fe IX], [Fe XIV], [Fe XV], and [S XII], are detected in nonradiative shocked ejecta (Seitenzahl et al. 2019); however, we will focus on only the strongest diagnostic lines in this paper. The line images extracted include those of H$\alpha$, [O III]...
Figure 3. (a) HST Hα and VLT MUSE Hα, [O III], [Fe XIV], [O I], and [S II] images of SNR 0509–67.5. (b) Same as panel (a), but with VLT MUSE Hα contours overplotted. In the [S II] image, an blue arrow points to a galaxy that is a residue from the spectral-background subtraction.

As these line images have the same FOV and image scale, they can be inter-compared directly to search for forbidden-line emission features. These Hα images can be compared with the HST Hα images for detailed physical structures of emission features. We note that some stars have negative values in the MUSE Hα line images because their spectra have the Hα line in absorption.

Finally, we analyze the spectral properties of the forbidden-line emission features, measuring their line strengths relative to Balmer lines and using the [N II] $\lambda5755/\lambda6583$ diagnostic to determine electron temperatures and the [S II] $\lambda6716/\lambda6731$ diagnostic to determine electron densities. These physical parameters are used to assess the physical conditions of the forbidden-line emission features in order to determine their origin.

4. Results of Individual Objects

The five Type Ia SNRs with Balmer-dominated shells we have studied are shown in Figure 1, where the same image scale is used for all five SNRs for easier inter-comparison. The results of our analyses of these five SNRs are described below. See the Appendix for representative spectra of different morphological features in the SNR and of the background interstellar medium (ISM), plotted in two wavelength ranges that cover the Hβ + [O III] lines and Hα + [N II] + [S II] lines, respectively.

4.1. SNR 0509–67.5 (Figure 3)

The HST Hα image of SNR 0509–67.5 exhibits an overall regular and slightly elliptical shell, as shown in Figure 3(a). The eastern side of the shell shows one major filament delineating the rim, indicating a simple shell structure, while the western side exhibits multiple filaments along the rim that has been suggested to be caused by a non-uniform ambient medium (Hovey et al. 2015). The bright filaments originate from locations where the sight line is tangent to the shock front,
while the diffuse emission near or between the filaments originates from locations where the shock front is oblique to the line of sight. No dense Hβ knots are seen in SNR 0509–67.5.

The MUSE Hα image of SNR 0509–67.5 detects not only the shell rim but also diffuse emission throughout the face of the SNR, including the central region where the SNR shocks propagate along the lines of sight and the emitting path lengths are the shortest. This image also detects a faint Hα halo just outside the SNR shell. This halo, not detected in the HST Hα image, most likely originates from the ambient medium photoionized by the UV precursor of the SNR shocks. Beyond the halo, to the east and southeast of the SNR exist three broad streamer-like features that are most likely from the interstellar background and are better seen in the [S II] image.

The MUSE [O III] line image shows some diffuse emission from the ISM background, but no [O III] emission from the Balmer shell or the halo around the shell. Note that the MUSE spectra show an emission line near λ5019–5022 Å, but this line corresponds to the Doppler-shifted He I λ5015 line.

The MUSE [Fe XIV] line image shows the reverse shock front into the SN ejecta. As illustrated in the color composite of Hα, X-ray, and [Fe XIV] images in Figure 1 of Seitenzahl et al. (2019), the Hα emission from the forward collisionless shock is located at the largest radius, the [Fe XIV] emission behind the reverse shock is located at the smallest radius, while the X-ray emission is sandwiched between these two shock fronts.

The MUSE [S II] line image shows a completely different picture from the Hα line image. Neither the filamentary Balmer shell nor the faint diffuse Hα halo is detected in [S II]. The most prominent [S II] emission appears in diffuse arcs and streamer-like features on scales larger than the SNR. The streamer-like features to the east of the SNR have counterparts in the MUSE Hα and [O I] line images. The irregular distribution of these [S II] features suggests that they originate from a background ISM.

The MUSE [O I] line image shows essentially the same kind of diffuse arcs and streamer-like features that are seen in the [S II] image. No [O I] emission can be unambiguously associated with the SNR per se.

The [S II] line strength relative to the respective nearest Balmer lines for the SNR and the interstellar background are given in Table 2. To determine the forbidden-line strengths at the Balmer shell rim, it is necessary to subtract the background. In the [S II] lines, the background is not only bright but also non-uniform. The [S II]/Hα ratio of the filamentary Balmer shell reported in Table 2 is derived by using a medium to low background value. If a higher background value is used, the [S II]/Hα becomes negative. The “;” symbol denotes a non-detection, and the error is dominated by the uncertainties in the background subtraction. The faint Balmer halo is not detected in [O III] or [S II], and the large variations in the background ISM emission make it impossible to make meaningful estimates of their upper limits. The [S II]/Hα ratio of the background ISM exhibits a range of values, as given in Table 2. The [S II]/Hα line ratio of the background is in the low-density limit, <100 H–atom cm$^{-3}$, consistent with an ISM origin.

Table 2
Representative Physical Quantities and Properties in and around SNRs with Balmer-dominated Shells

| SNR   | Age (yr) | Features   | [S II]/Hα | [O III]/Hβ | n_e (cm$^{-3}$) | T (K) |
|-------|---------|------------|-----------|------------|----------------|-------|
| 0509–67.5 | 400 ± 50$^b$ | Filamentary Shell | (0.9–1.5) ± 1 | ... | ... | ... |
| 0519–69.0 | 600 ± 200$^b$ | Bright Knots | (0.2–1.5) ± 0.2 | ... | ... | ... |
| N103B | 860$^b$ | Filamentary Shell | (0.1–0.5) ± 0.1 | ... | ... | ... |
| DEML71 | 4360 ± 290$^c$ | Bright Knots | (0.2–1.3) ± 0.1 | ... | ... | ... |
| 0548–70.4 | ~10,000$^d$ | Filamentary Shell | (0.3–0.7) ± 0.1 | ... | ... | ... |

Notes.

$^a$ Integrated Hα fluxes measured from the MUSE data are: 1.5 × 10$^{-13}$, 2.9 × 10$^{-13}$, 1.2 × 10$^{-12}$, and >6.7 × 10$^{-13}$ erg s$^{-1}$ cm$^{-2}$ for 0509–67.5, 0519–69.0, N103B, and DEM L71, respectively. Note that the MUSE field is too small to cover the entire DEM L71 and the Hα flux of DEM L71 represents only a lower limit.

$^b$ From Rest et al. (2005).

$^c$ From Ghavamian et al. (2003).

$^d$ Very few knots have [N II] λ5755 line clearly detected.

$^e$ From Hendrick et al. (2003).
4.2. SNR 0519–69.0 (Figure 4)

The HST Hα image of SNR 0519–69.0 shows a more complex morphology than that of 0509–67.5. The SNR shell rim from east through south and west to north is roughly round, with morphological features suggestive of a “bubbly” shell surface. The northeastern quadrant of the SNR shell rim appears flattened; however, in this direction a faint filamentary arc is detected at larger distances than the average shell radius in the other quadrants. It is likely that the faint outer arc represents the shock front in the northeastern quadrant, while the bright, flattened filament and the bright interior semi-straight filament in the southwestern quadrant may have formed by the same mechanism. No dense knots similar to those in N103B are seen in this Hα image of SNR 0519–69.0.

SNR 0519–69.0’s MUSE Hα line image shows a qualitatively similar morphology at a lower resolution than its HST Hα image (see Figure 4). The MUSE Hα image detects emission over the face of the SNR and slightly beyond the SNR radius, similar to what is seen in 0509–67.5, although the diffuse Hα halo of 0519–69.0 is not as extended. This diffuse Hα halo is marginally detected in the HST Hα image. Similarly, this halo most likely originates from an ambient medium photoionized by the SNR shock’s UV precursor, as in the case of 0509–67.5. Beyond the halo, SNR 0519–69.0 is surrounded by diffuse, patchy Hα emission associated with ambient or background ISM.

The MUSE [O III] line image reveals a small patch of emission in the SNR interior and this patch is much more prominent in the [S II] and [O I] lines images, as shown later in this section. This [O III] image also shows a very weak partial counterpart of the Balmer shell: detected from the east through the south to the southwest along the bright rim and possibly along the faint outer rim in the southwest quadrant. We have carefully separated the [O III] line emission from the He I λ5015 line emission; however, the faint high-velocity wings may overlap and contribute to low-level contamination in limited regions where both lines are detected. No [O III] counterpart of the faint Hα halo is detected. [O III] emission from the diffuse background ISM is detected to the north and to the south of the SNR.

The [Fe XIV] line image shows a shell associated with the reverse shock front into the SN ejecta, similar to that seen in SNR 0609–67.5. However, 0619–69.0 shows two additional patches of [Fe XIV] emission, marked by arrows in Figure 4(b). The east patch is projected near the brightest part of the Balmer shell’s eastern rim, while the north patch is projected near the one o’clock position of the [Fe XIV] ring. These two small patches have a different origin from the [Fe XIV] shell associated with the reverse shock, as the FWHM of the line profile is ~300 km s\(^{-1}\) in the patches and a few ×10\(^3\) km s\(^{-1}\) in the shell. The north patch emits brightly in [O I] and [S II] and faintly in [O III]; the east patch shows [O III] and [O I] emission.
but it is difficult to disentangle the contributions from the Balmer shell and the east patch.

The [S II] line image reveals two distinct knots of bright emission projected within the SNR shell, about halfway from the shell center to the bright Hα shell rim in the north. These [S II] knots are coincident with the north patch of [Fe XIV] emission, and have faint counterparts in the [O III] line image, too. In the MUSE Hα image, these knots blend in with Balmer filaments and do not appear as distinct features; however, the HST Hα image reveals that the two knots are connected by diffuse emission of lower surface brightness and the knots have diameters of \( \sim 0.3 \) (0.075 pc). These nebular knots are so small that they easily escape detection if the HST Hα image alone is examined. The presence of these isolated small knots is very intriguing and their origin will be discussed later in this paper.

Besides these knots, no [S II] emission can be unambiguously associated with the SNR shell or the faint Hα halo, although an irregular diffuse ISM emission background is clearly detected.

The [O I] line image shows not only bright counterpart of the north [Fe XIV] patch that is coincident with the [S II] knots, but also enhanced emission at the east [Fe XIV] patch that is not detected in [S II]. In addition, [O I] emission is seen along the southern half of the Balmer shell rim. There is enhanced [O I] emission enclosed within the northern part of the Balmer shell, but it is not clear whether the [O I] emission is associated with the SNR shell or the background diffuse ISM.

The [O III] and [S II] line emission from the Balmer shell and the background ISM of 0519–69.0 is measured in a similar fashion as that of 0509–67.5. The two dense knots in 0519–69.0 are measured with very high signal-to-noise ratios. The [S II]/Hα and [O III]/Hβ ratios of the Balmer shell, dense knots, and the background ISM are given in Table 2. The [S II] doublet ratio of the background is in the low-density limit and consistent with an ISM origin.

4.3. SNR N103B (Figure 5)

The HST Hα image of SNR N103B clearly reveals a filamentary shell structure that encompasses prominent groups of dense knots. Only the filamentary shell is Balmer-dominated, and the dense knots represent a CSM ejected by the SN progenitor (Williams et al. 2014; Li et al. 2017). The shell is elliptical with an opening to the east. The knots are mainly distributed in four groups, with only a few knots located along Hα filaments near the shell rim. Almost all knots are seen on the western side of the shell interior. The knots individually can have sizes as small as 0.14\( ^\prime\) (0.035 pc) in diameter, while a group of knots can be as extended as 2\( ^\prime\) (0.5 pc) across.

N103B’s MUSE Hα line image shows bright nebular knots in the interior of an incomplete shell, similar to those seen in the HST Hα image, except the “knots” seen in the MUSE image correspond to “groups of knots” in the HST image (see Figure 5). The MUSE Hα image also shows that N103B is projected in a
complex diffuse background with multiple filaments and arcs in the surroundings.

The MUSE [O III] line image shows bright emission from the knots, and very faint emission from the Balmer-dominated shell. The surrounding ionized ISM is also detected in the [O III] image with a surface brightness distribution following that of the Hα image roughly but not exactly. The [O III]/Hα ratio varies among the CSM knots and in the surrounding ISM; their values are given in Table 2.

The MUSE [Fe XIV] line image shows bright emission from the CSM knots and an arc extending to the east. This arc has no counterpart in other optical line images; however, it follows an X-ray arc closely (Seitenzahl et al. 2019). The FWHM of the [Fe XIV] line profile is up to 3300 km s\(^{-1}\) in the arc, and 400 km s\(^{-1}\) in the knots. These widths and spatial distributions are consistent with the origin of the reverse shock into the SN ejecta for the arc and forward shock into the CSM for the knots.

The MUSE [S II] line image shows bright emission from the CSM knots and an arc extending to the east. This arc has no counterpart in other optical line images; however, it follows an X-ray arc closely (Seitenzahl et al. 2019). The FWHM of the [Fe XIV] line profile is up to 3300 km s\(^{-1}\) in the arc, and 400 km s\(^{-1}\) in the knots. These widths and spatial distributions are consistent with the origin of the reverse shock into the SN ejecta for the arc and forward shock into the CSM for the knots.

The MUSE [O I] image shows bright emission from the CSM knots. The background emission from diffuse ISM is also detected at a much lower level than the CSM knots.

In summary, N103B has prominent forbidden-line emission from the CSM knots, faint [O III] line emission from the Balmer-dominated shell, and moderately bright forbidden-line emission from the surrounding ISM. The representative ranges of forbidden-line strengths from different features in and around the SNR N103B are given in Table 2. The dense knots’ electron densities determined from the [S II] doublet are \(10^3 – 10^4\) cm\(^{-3}\), consistent with the \(3 \times 10^4 – 10^5\) cm\(^{-3}\) determined from the UV lines of Si ii (Blair et al. 2020), and their electron temperatures determined from the [N II] lines are 10,000–20,000 K. The electron density of the background is below 100 cm\(^{-3}\), consistent with an ISM origin.

4.4. SNR DEM L71 (Figure 6)

The HST Hα image shows that DEML71’s SNR shell is quite irregular. The eastern and southwestern sides of the shell contain interior filaments curved along the outer rim. The northern and southwestern parts of the shell rim bulge out, suggestive of blow-outs into a lower-density medium. Upon closer inspection, small knots can be seen distributed along some interior filaments and outer rim. The smallest nebular knots have diameters of \(0.075\) pc. A small number of nebular knots are projected in the shell interior, and they appear diffuse with lower surface brightness.

DEML71’s MUSE Hα line image has a smaller field of view than the HST Hα image. In the MUSE Hα image, the eastern part of the main SNR shell is clearly detected but the shell rims...
and the Balmer shell rim on the east side. The SNR 0548
The MUSE
knots near the east rim and northwest rim. In addition,
the west curved along the shell rim from the east through the south to
fi
Figure 7. (a) HST Hα and ATT WiFeS Hα, [O III], [Fe XIV], [O I], and [S II] images for the G9 data of SNR 0548–70.4. The green square marks the region shown in Figure 8, which illustrates the morphology of knots.

in the other directions are outside the field of view. The MUSE Hα image, being much deeper than the HST Hα image, reveals numerous filamented within the SNR shell, especially those curved along the shell rim from the east through the south to the west (see Figure 6). In addition, some Hα nebular knots are detected.

The MUSE [O III] line image shows a very different morphology: bright knots are detected along the aforementioned curved filaments interior to the shell, and some knots are projected in the central cavity without association with filaments. The [O III] image also detects faint counterpart of the eastern rim of the Balmer-dominated shell. Also detected is a band of diffuse emission extending from the top center southwestwards to the bottom of the field of view.

The MUSE [Fe XIV] line image shows emission from the knots near the east rim and northwest rim. In addition, [Fe XIV] emission is detected along the Balmer shell rim on the east and west sides of the SNR. It is interesting that the [Fe XIV] arcs follow X-ray emission that delineates the forward shocks into the ISM. This is quite different from what we see in 0509–67.5, 0519–0.063 pc, and N103B.

The MUSE [S II] line image shows nebular knots even more prominently than the [O III] image, detecting more faint knots. The MUSE [S II] image also detects faint emission from the Balmer-dominated shell rim on the east. The [S II] image of DEML71 has also detected the northern part of the band of diffuse emission seen in the [O III] image.

The MUSE [O I] line image shows emission from both knots and the Balmer shell rim on the east side. The [O I] image is qualitatively similar to the [S II] image, although the [O I] emission along the Balmer shell rim is more prominent.

The MUSE observation of DEML71 covered only a small area of sky outside the SNR shell. While this sky coverage is adequate for background subtraction from bright features of small sizes, such as the Balmer shell rim and knots, it is inadequate for accurate measurements of forbidden-line emission from the background per se or background subtraction for extended features, such as the band of diffuse emission across the face of DEML71. Therefore, only the Balmer shell and the knots are reported in Table 2. The electron densities of the knots are in the range from 650 to over 10,000 cm−3, and the electron temperatures are ∼13,000 K. The electron density derived from the [S II] doublet of the SNR shell rim is in the low-density limit, <100 cm−3.

4.5. SNR 0548–70.4 (Figures 7(a) and (b))

The HST Hα image of SNR 0548–70.4 has the lowest signal-to-noise ratio compared to similar observations of N103B and DEML71, because of the relatively low surface brightness of 0548–70.4. The Balmer-dominated shell of 0548–70.4 appears quite regular (see Figure 1), although it shows double-rim morphology along the northeastern quadrant, similar to those seen in DEML71. Projected near the central region of 0548–70.4 are four strips of diffuse emission with some of them containing nebular “rods” that are 0″25 (0.063 pc) in width and up to 2″ (0.5 pc) in length. There is also enhanced nebular emission, possibly similar to knots or rods, along a filament near the northwestern rim.

The ATT WiFeS observations of SNR 0548–70.4 mapped the entire remnant (Figure 2); however, only data of the G4 and G9 fields are of adequate quality to extract spectral information. The G9 field includes a segment of the Balmer-dominated shell rim and one of the four aforementioned strips of diffuse emission in the central region of the SNR (Figure 7(a)). The [O III], [O I], and [S II] line images detect emission from knots and the strip of diffuse emission, but the Balmer-dominated shell rim is not unambiguously detected in any of the forbidden-line images. The [Fe XIV] line is not detected anywhere. The G4 field includes strips of diffuse emission with embedded knots (Figure 7(b)). These features are detected in [O III], [O I], and [S II] line images. The [Fe XIV] line is not detected. The relative strengths of the [O III], [O I], and [S II] lines vary among the emission regions. The ranges of
representative \([\text{O III}]/\text{H}\beta\) and \([\text{S II}]/\text{H}\alpha\) ratios are given in Table 2.

5. Discussion

5.1. Dense Knots

5.1.1. Physical Properties of the Knots

The content and distribution of dense knots are different among the five Type Ia SNRs with Balmer-dominated shells we studied: in ground-based [S II] images, 0509–67.5 has no knots at all, 0519–69.0 has two knots close together in the northwest quadrant of the SNR, N103B has prominent groups of knots distributed only in the west side of the SNR, DEM L71 has bright knots distributed along inner Balmer filaments in a ring-like structure with fainter knots projected interior to the ring, and 0548–70.4 has knots distributed mostly within a few patches projected near the central region of the SNR.

The “knots” detected in ground-based images are often resolved into multiple smaller knots in HST images. The morphologies of these small knots are different among the SNRs. HST H\(\alpha\) images show that some knots are round or slightly elongated with minor axis as small as \(\sim 0''/2\) and major-to-minor axis ratio ranging from 1.0 to a few, as seen in N103B and DEM L71, while some knots are rod-like with widths of \(\sim 0''/2\) and lengths of \(2''\)–\(3''\), as seen in 0548–70.4. The knots in 0519–69.0 are best detected in the MUSE [O I] and [S II] line images where two knots are seen. The HST H\(\alpha\) image resolved these knots into knots as small as \(0''/3\) (0.075 pc) in diameter and connecting filaments. The different morphologies of knots are illustrated in Figure 8.

The spectral properties vary among the knots as well. The variations can be easily seen from comparisons among the line images. For example, N103B and DEM L71 have knots that are well detected in [O III] but appear very faint in [S II], and vice versa. Most interestingly, of the two [Fe XIV] knots in 0519–69.0 (marked in Figure 4, one is bright in [S II] and [O I] but faint in [O III], while the other has faint counterparts in [O I] and [O III] but not detected in [S II].

Electron densities of the knots, determined from the [S II] \(\lambda 6716/\lambda 6731\) ratios, range from a few \(10^2\) to \(10^3\) cm\(^{-3}\). 0548–70.4 has the lowest density in the knots, which also have the rod-like morphology.

The [O III]/\(\text{H}\beta\) ratios of the knots range from 0.2 to 5.6: 0519–69.0 and N103B have lower values in general, and DEM L71 and 0548–70.4 extend to higher values (see Figure 9). The [S II]/H\(\alpha\) ratios of the knots range from 0.1 to 1.3. The low values of [S II]/H\(\alpha\) ratio are associated with the densest knots whose high densities, \(\gtrsim 10^4\) cm\(^{-3}\), exceed the critical densities of the [S II] \(\lambda\)6716, 6731 lines, as seen in Figure 10 and elaborated later in Section 5.1.2.

The [N II] \(\lambda 5755/\lambda 6584\) ratios can be used to diagnose electron temperatures. The weak [N II] \(\lambda 5755\) line is detected only in knots of N103B and DEM L71. N103B has a large number of bright knots and their electron temperatures range from 9000 to 19,000 K. In DEM L71 only the very few brightest knots are detected in the [N II] \(\lambda 5755\) line and their temperatures are \(\sim 11,000\) K.

5.1.2. Origin and Implication of the Knots

The knots resolved in HST H\(\alpha\) images of these five Type Ia SNRs are small, dense, and H-rich. The size, as small as 0.05 pc, and density, as high as \(\gtrsim 10,000\) H cm\(^{-3}\), are not characteristic for the ISM. In the HST program 13282, H\(\alpha\) images of four
larger and more evolved Type Ia SNRs are available—0454−67.2, DEM L238, DEM L249, and DEM L316A. None of these Type Ia SNRs show small dense knots in their interiors or along their shell rims. The HST archive has Hα and/or [O III] images of six core-collapse SNRs in the LMC—N49, N63A, and N206 from program 8110, 0540−69.3 from programs 6120 and 7340, and N132D from program 12001, and SN1987A from multiple programs. Among these, only N63A and N132D have small features that can be compared with the knots seen in the 5 Type Ia SNRs we have studied. Figure 8 shows that the cloudlets in N63A and N132D are qualitatively similar to the knots in the Type Ia SNRs, and they are known to be interacting with molecular clouds (Sano et al. 2019, 2020). However, the rms electron densities in the cloudlets in N63A and N132D have small features that can be compared with the knots seen in the 5 Type Ia SNRs we have studied. Figure 8 shows that the cloudlets in N63A and N132D are qualitatively similar to the knots in the Type Ia SNRs, and they are known to be interacting with molecular clouds (Sano et al. 2019, 2020). However, the rms electron densities in the cloudlets in N63A are 150–700 cm$^{-3}$ (Chu et al. 1999) and the electron densities of the knots in N132D are generally 2000–4000 cm$^{-3}$ (Dopita et al. 2018), much lower than what we see in the knots in Type Ia SNRs with Balmer-dominated shells. SN1987A is transitioning from an SN to an SNR, and only the knots in its inner ring have sizes $\sim 0.03$ pc and densities 1000–30,000 atoms cm$^{-3}$ (Mattila et al. 2010), comparable to the knots we see in Type Ia SNRs. The rings around SN1987A are known to be of a CSM origin. We thus consider that the small knots observed in the Type Ia SNRs with Balmer-dominated shells most likely belong to a CSM.

The dense knots in 0519−69.0 are not as numerous and wide-spread as those in N103B, DEM L71, and 0548−70.4. The brightest ones are concentrated in a small 0′.5 $\times$ 3′ (0.13 pc $\times$ 3 pc) patch, coincident with the north patch of [Fe XIV] emission. The east patch of [Fe XIV] emission may also be associated with dense knots; however, it is superposed on a very bright Balmer shell rim and its counterparts in [O I], [O III], and [S II] lines are all quite weak. It is likely that the dense knots in 0519−69.0 have a different origin from those in the other three SNRs. Without further information, such as kinematics and elemental abundances, about the knots in 0519−69.0, we cannot confidently assess how this CSM material was ejected or has evolved. We will thus discuss below mainly knots in the other three Type Ia SNRs.

Because of the high density in the knots, their recombination timescales are short. For example, the recombination timescale is 70 yr for a density of 1000 H cm$^{-3}$ and only 7 yr for a high density of 10,000 H cm$^{-3}$. Depending on the propagation of the SNR shocks, different sets of knots should brighten up and fade as time goes on, much like the knots in SN1987A’s inner ring (Fransson et al. 2015). Indeed, the HST Hα images of N103B taken on 2013 July 11 and 2017 January 3 show some knots faded and some knots brightened up, as illustrated in Figure 11.
To inter-compare the knots from the Type Ia SNRs, we first examine their \([\text{S II}] / \text{H} \alpha\) ratio as a function of density in Figure 10. The horizontal axis is \([\text{S II}] \lambda 6716 / \lambda 6731\), which is a diagnostic for electron densities. Beside the clear separation of the ISM and CSM densities, it is striking that the knots in N103B, DEM L71, and 0548–70.4 are segregated in the density distribution. N103B is the smallest and has the densest knots, while 0548–70.4 is the largest and has the least dense knots. This trend is suggestive of an evolutionary effect: as an SNR evolves and expands to larger size, its CSM knots go through ionization and shock interactions and become less dense. It is also noticeable that the greatest majority of the knots in Figure 10 follow the trend that the highest observed \([\text{S II}] / \text{H} \alpha\) ratio for any specific \([\text{S II}] \lambda 6716 / \lambda 6731\) decreases with decreasing \([\text{S II}] \lambda 6716 / \lambda 6731\), or increasing density. This trend is caused by the low critical densities of the \([\text{S II}]\) lines, 1585 and 3981 cm\(^{-3}\) for \(\lambda 6716\) and \(\lambda 6731\), respectively.

The \([\text{O III}] / \text{H} \beta\) ratio versus \([\text{S II}] \lambda 6716 / \lambda 6731\) ratio plot in Figure 9 shows contrasting distributions among the SNRs. N103B has very few knots with \([\text{O III}] / \text{H} \beta > 2\), while DEM L71 has a significant fraction of knots with \([\text{O III}] / \text{H} \beta > 2.0548–70.4, unlike N103B and DEM L71, has no knots with \([\text{O III}] / \text{H} \beta < 0.5\). These differences may also be caused by their evolutionary status associated with the passage of SNR shocks. The large spreads of \([\text{O III}] / \text{H} \beta\) ratios in 0548–70.4 and DEM L71 probably requires incomplete shocks, as suggested by the variability of some of the knots mentioned in Section 5.1.2. It is hard to get \([\text{O III}] / \text{H} \beta\) above 2 or 3 except by having an incomplete recombination zone. The very low \([\text{O III}] / \text{H} \beta\) ratios in some of the N103B knots (below about 0.2) suggest very slow shocks, less than 100 km s\(^{-1}\).

It is tempting to conclude that N103B, DEM L71, and 0548–70.4 all contain dense CSM and have single-degenerate SN progenitors, although surviving companions of the progenitors have not been successfully identified (Li et al. 2019). The absence of an abundant CSM in 0509–67.5 and 0519–69.0 has been used to argue that their SN progenitors...
were likely of double-degenerate origin, especially since the young 0509–67.5 has no viable stellar candidate for its SN progenitor’s companion near the center of the SNR (Schaefer & Pagnotta 2012; Litke et al. 2017). However, the discovery of knots in 0519–69.0 raises question about their origin, which may not be entirely clear at present.

5.2. Collisionless Shocks of the Balmer Shells

Both 0509–67.5 and 0519–69.0 have been well studied: their shock speeds have been measured from HST proper motions by Hovey et al. (2018) and their ambient preshock densities have been derived from dynamical models by Seitenzahl et al. (2019). We will focus on the case of 0519–69.0 because its [O III] emission is detected and the [O III]/Hβ ratio has a high S/N. We adopt shock speeds of 1300–2500 km s⁻¹ and a preshock density of 1.5 amu cm⁻³ from the above references. We assume the hydrogen to be 50% neutral because if it were highly ionized the Balmer filaments would be correspondingly faint, and because helium atoms swept up by the shock produce enough photons to ionize at least 30% of the hydrogen. We concentrate on [O III], but generally similar considerations would apply to [S II].

Balmer-line filaments show essentially pure Balmer-line spectra in the optical range. The hot gas behind the shock efficiently excites neutral H atoms that pass through the shock before they can be ionized. Thus the profiles of the Balmer lines show two components: a broad component whose width is related to the postshock proton temperature and a narrow component whose width reflects the preshock temperature. For postshock temperatures of 10⁶ K or more, each neutral hydrogen atom produces about 0.25 Hz and about 0.05 Hβ photons on average before it is ionized. By comparison, there are several thousand times fewer oxygen atoms than hydrogen, so the forbidden lines that dominate most SNR shock wave spectra are expected to be faint.

Most shocks in the ISM except for C-shocks (Draine et al. 1983) are collisionless, meaning that the shock transition is governed by magnetic fields and plasma turbulence. The shock thickness is determined by the proton gyroradius or the ion skin depth, which are far smaller than the particle mean free path. Because the bulk velocities of particles entering the shock are randomized by plasma processes rather than collisions, they do not reach thermal equilibrium. Instead of Maxwellian velocity distributions, both electrons and ions can show high-energy tails as a result of diffusive shock acceleration (Blandford & Eichler 1987), and different particle species can have different temperatures. In shocks faster than 1000 km s⁻¹, electron temperatures T_e are only a few percent as high as the proton temperatures T_p (Ghavamian et al. 2001, 2013), and ion temperatures T_i tend to be proportional to ion mass m_i, T_i ∼ (m_e/m_i)T_p (Korreck et al. 2004; Raymond et al. 2017). The collisionless nature of these shocks also explains the two-component Balmer-line profiles. Some neutrals pass through the shock unaffected, so when they are excited they produce emission with the preshock velocity profile. Others experience charge transfer with a postshock proton, and when they are excited they produce a correspondingly broad profile.

There are two possible origins for the [O III] emission. It could be produced in a narrow ionization zone just behind the shock in the same manner as the Balmer lines, or it could arise from a shock precursor. If the [O III] were produced in the shocked gas, the line would be very broad. Since there is little thermal equilibration in such fast shocks, the FWHM of the emission from 0519–69.0 would be similar to the shock speeds of 1300 km s⁻¹ at the E limb and 2500 km s⁻¹ at the S limb, or 25–60 Å. That would mean that little of the emission would be within the 8 Å band of the [O III] image, and the emission in the off-band image that is subtracted would nearly cancel out what remains.

Given an LMC oxygen to hydrogen ratio of 0.0002–0.0003 (Russell & Dopita 1992) and an emission rate of 0.05 Hβ photons per hydrogen atom, the observed [O III] to Hβ ratio of 0.011 would require about 0.7 [O III] photon per O atom. At very high temperatures, the number of photons is given by the ratio of excitation rate to ionization rate. We take excitation and ionization rates by electrons from CHIANTI version 8 (Dere et al. 1997; Del Zanna et al. 2015) and we assume that the excitation rate by protons is about equal to that by electrons at T_e = (m_e/m_i)T_i to find that each O atom should produce 0.3–0.5 [O III] photons. It therefore seems that the postshock region could produce almost the observed [O III] intensity if the intensity were not spread over a band much wider than that used to generate Figure 4. We conclude that the [O III] emission in 0519–69.0 cannot come from the postshock gas.

The alternative emission region is a shock precursor. Three kinds of precursor can be present: a photoionization precursor, a cosmic-ray precursor associated with diffusive shock acceleration (Blandford & Eichler 1987; Boulares & Cox 1988), or a precursor produced by broad component neutrals overtaking the shock and depositing their energy upstream (Hester et al. 1994; Morlino et al. 2012). Precursors have been inferred from Hα narrow components that are broader than would be consistent with a significant neutral fraction in equilibrium, indicating that the gas is heated in a narrow precursor just ahead of the shock (Hester et al. 1994), and they can be seen as faint emission ahead of the main shock in Tycho’s SNR (Lee et al. 2010). The proton kinetic temperatures indicate narrow component widths ranging from about 3 × 10⁴ to 10⁶ K (Sollerman et al. 2003; Medina et al. 2014; Knežević et al. 2017), but the electron temperatures are poorly constrained. The precursor thickness ranges from 0.3 × 10¹⁶ to 3 × 10¹⁶ cm (Lee et al. 2010; Katsuda et al. 2016). Photoionization precursors associated with Balmer-line filaments have been reported for Tycho’s SNR (Ghavamian et al. 2000) and the Cygnus Loop (Medina et al. 2014). The photoionization is dominated by He I and He II photons near 21 and 40 eV, respectively, and they heat the gas to around 17,000 K.

The existence of the Balmer-line filaments implies a substantial neutral hydrogen fraction in the upstream gas. O III does not coexist with neutral H because of the very rapid charge transfer process H⁺ + O → H+ + O²⁻, which has a rate coefficient of 1.0 × 10⁻²⁶ cm³ s⁻¹ (Kingdon & Ferland 1996). Therefore, oxygen must be ionized to O III in the precursor. It cannot be collisionally ionized, because hydrogen would be more rapidly ionized, and no neutral atoms would reach the shock to produce the Hα broad component. However, O III can be produced by photoionization by He II λ304 photons, because the photoionization cross section of O²⁻ at a photon energy of 40 eV is 30 times larger than that of H⁺ (Reilman & Manson 1986). For a density of 1.5 cm⁻³ and 80% ionization, the lengths for absorption by a mixture of H and He correspond to 1/5 and 7/8 for He I and He II photons, respectively. The latter is similar to the precursors seen in the E and S limbs of Figure 4, while the former is compatible with the thickness of the [O III] emitting region, though that may be
dominated by projection effects rather than the physical thickness. The flux of He II \( \lambda 304 \) photons from the shock is proportional to the number of He atoms swept up per second, and therefore to the shock speed. Only shocks faster than about 1000 km s\(^{-1}\) produce enough photons to dominate over the charge transfer rate, which explains why [O III] is detected in the fastest shocks.

To evaluate the different roles of neutral and cosmic-ray precursors, we calculate the temperature ahead of the shock with and without cosmic rays acceleration. We use the model developed by Morlino et al. (2013) which allows us to calculate the shock structure in the presence of both neutral H and cosmic rays. For all cases analyzed we assumed a shock velocity of 2500 km s\(^{-1}\) and an ambient density of 1.5 cm\(^{-3}\). Figure 12 shows the resulting temperature profile of H ions ahead of the shock. The top panel shows the cases without cosmic rays where we change the neutral fraction from 10% up to 50%. The precursor temperature increases with increasing neutral fraction as a consequence of the larger number of neutrals returning from the downstream. For a neutral fraction \( \approx 50\% \) the precursor temperature is \( \sim 10^7 \) K hence it would be enough to efficiently excite O III. Nevertheless the precursor thickness is only \( \lesssim 10^{16} \) cm (corresponding to \( 0.5013 \)), roughly an order of magnitude smaller than the excitation lengthscale for O. Moreover, the very efficient heating by backstreaming neutrals raises the temperature to about \( 10^7 \) K, and at that temperature O III is ionized more rapidly than it is excited.

The bottom panel of the same figure shows, instead, the impact of including cosmic-ray acceleration. We assume that the acceleration efficiency is only 5%, in order to be compatible with the upper limit of \( \sim 7\% \) found by Hovey et al. (2018) and that the maximum energy of accelerated protons reaches \( E_{\text{max}} = 1 \text{ TeV} \). Such energies can be reached if the diffusion coefficient is Bohm-like in a \( \sim 1 \mu G \) field. Notice that the maximum extent of the cosmic-ray precursor corresponds to the propagation length scale at \( E_{\text{max}} \), which is \( \ell_d = D_{\text{Bohm}}(E_{\text{max}}, 1 \mu G) / \sqrt{\eta} \approx 4 \times 10^{19} \) cm. We show two cases where the neutral fraction is fixed to 50% but the wave damping rate changes from \( \eta_{\text{AH}} = 0.1 \) to 0.3. The parameter \( \eta_{\text{AH}} \) is the fraction of magnetic waves’ energy (excited by cosmic rays) which is damped to thermal energy of the plasma and determines the final precursor temperature. It is worth noting that similar temperature profiles can be obtained for different combinations of acceleration efficiency, \( \eta_{\text{AH}} \), \( E_{\text{max}} \) and magnetic field. But, what is important in this context is that, for reasonable values of the parameters (even for relatively small acceleration efficiency), the precursor temperature starts increasing already at a distance larger than \( 10^{17} \) cm, making possible the effective collisional excitation of O III lines.

We conclude that photoionization is responsible for the presence of O \( ^{++} \) in the gas upstream of the shock, but heating by the cosmic-ray precursor, and to a lesser extent by the return neutral precursor, increases the temperature and doubles the excitation rate of the O III transitions. For the excitation rate at temperatures of 20,000–40,000 K and a preshock density of 1.5 cm\(^{-3}\), the observed [O III] flux in 0519–69.0 indicates an O III ionization fraction of around 5%–20%. Thus all three types of precursor contribute to the observed [O III] brightness.

### 6. Summary

Five Type Ia SNRs with Balmer-dominated shells are known in the LMC: 0509–67.5, 0519–69.0, N103B, DEM L71, and 0548–70.4. We have been using HST images and VLT MUSE observations of these SNRs to search for surviving companions of their SN progenitors (Li et al. 2017, 2019; Litke et al. 2017). In the course of this work, we find prevalent forbidden emission from these Type Ia SNRs. Three types of forbidden-line emission are detected: bright [O III], [O I], [S II], etc. and faint [Fe XIV] emission from shocked dense knots interior to the SNR shells, [Fe XIV] and similar high Fe ion lines from reverse shocks into the SN ejecta, and faint [O III] and other low-ionization line emission from the Balmer shells.

Small dense knots are detected in all except 0509–67.5. MUSE spectra of the knots show bright forbidden-line emission from [O III], [N II], [S II], etc. Electron densities determined from the [S II] \( \lambda 6716/\lambda 6731 \) doublet ratio ranges from a few hundred to \( \gtrsim 10^4 \) cm\(^{-3}\). The knots can be slightly elongated or rod-like with major-to-minor axis ratios greater than 10. As the densities exceed the critical densities of the [S II] \( \lambda 6716, 6731 \) lines, the [S II]/H\(_\alpha\) ratio decreases at high densities and reaches as low as 0.1. The high density and small size of the knots are not characteristics of ISM; thus, the knots must have a CSM origin.

The recombination timescale for the dense knots are below 10 years, and indeed brightness variations in knots can be seen in the HST images of N103B from two epochs separated by 3.5 yr. Physical properties of the dense knots vary among the five Type Ia SNRs we studied; the variations appear to be correlated with the SNR ages (in the second column of Table 2). 0509–67.5 has no knots at all, 0519–69.0 has a small patch of knots and possibly another faint patch, N103B has the most prominent knots, DEM L71 displays knots near the shell rim, and 0548–70.4 has knots already shredded and disperse. It is conceivable that as time goes on, the CSM knots will be shocked to light up, then recombine and dissipate. The presence of CSM in Type Ia SNRs could be more prevalent than we previously thought.

The faint [O III] line emission from the Balmer shell is detected in VLT MUSE observations of SNRs 0519–69.0, N103B, and DEM L71. The ATT WiFeS observations of 0548–70.4 have too limited spatial coverage to determine whether this SNR also has [O III] emission from its Balmer shell. We focus on the case of 0519–69.0 because its [O III] emission is well measured and its shock velocity and ambient ISM density have been studied in detail and reported by Hovey et al. (2018) and Seitenzahl et al. (2019). We exclude the postshock origin of the [O III] emission because its FWHM is not compatible with the broad component of the Balmer lines. For the preshock origin, we considered three possibilities: photoionization precursor, cosmic-ray precursor, and neutral precursor. With considerations of the [O III]/H\(_\beta\) ratio and thickness of the [O III] shell, we conclude that the [O III] emission arises from oxygen that has been photoionized by [He II] \( \lambda 304 \) photons and is then collisionally excited in a shock precursor heated mainly by cosmic rays. A more detailed quantitative analysis of the nebular lines in these Type Ia SNRs will be carried out and reported in a future paper.
Appendix

We have analyzed VLT/MUSE or AAT/WiFeS observations of five Type Ia SNRs with Balmer-dominated shells in the LMC: 0509−67.5, 0519−69.0, N103B, DEM L71, and 0548−70.4. The representative spectra of different morphological features in the SNR and of the background ISM are shown in the Figures 13 and 14.

Figure 13. The spectra obtained from VLT MUSE and ATT WiFeS observations showing the representative [O III]/Hβ ratios in and around SNRs with Balmer-dominated shells. In each panel, all emission lines fluxes are normalized to the Hβ line. Knots A and B are examples with contrasting [O III]/Hβ ratios.
Figure 14. The spectra obtained from VLT MUSE and ATT WiFeS observations showing the representative [S II]/Hα ratios in and around SNRs with Balmer-dominated shells. In each panel, all emission lines fluxes are normalized to the Hα line. Knots A and B are examples with contrasting [S II]/Hα ratios.

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