A Morphological Study of the Supernova Remnant RX J0852.0–4622 (Vela Jr.)

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Abstract

We conduct a multiwavelength morphological study of the Galactic supernova remnant (SNR) RX J0852.0–4622 (also known as Vela Jr., Vela Z, and G266.2–1.2). RX J0852.0–4622 is coincident with the edge of the larger Vela SNR causing confusion in the attribution of some filamentary structures to either RX J0852.0–4622 or its larger sibling. We find that the RX J0852.0–4622 radio-continuum emission can be characterized by a two-dimensional shell with a radius of 0.90 ± 0.01 (or 11.8 ± 0.6 pc at an assumed distance of 750 pc) centered at (l, b) = (133°08±0°01, −46°34±0°01) (or R.A. = 8h52m19.2s, decl. = −46°20′24″, J2000), consistent with X-ray and gamma-ray emission. Although [O III] emission features are generally associated with the Vela SNR, one particular [O III] emission feature, which we denote as “the Vela Claw,” morphologically matches a molecular clump that is thought to have been stripped by the stellar progenitor of the RX J0852.0–4622 SNR. We argue that the Vela Claw feature is possibly associated with RX J0852.0–4622. Toward the northwestern edge of RX J0852.0–4622, we find a flattening of the radio spectral index toward another molecular clump also thought to be associated with RX J0852.0–4622. It is currently unclear whether this feature and the Vela Claw result from interactions between the RX J0852.0–4622 shock and interstellar medium gas.

Key words: acceleration of particles – gamma rays: ISM – ISM: supernova remnants – radio continuum: ISM

1. Introduction

The Galactic supernova remnant (SNR) RX J0852.0–4622 was first discovered in 1998 (Aschenbach 1998), and studies of a tenuous detection of the radioactive decay line of 44Ti suggested RX J0852.0–4622 to be young (∼680 years) and nearby (∼200 pc) (Iyudin et al. 1998). The 44Ti detection was and remains controversial (Renaud et al. 2006). More recent studies estimate ages of ∼1–3 kyr and 2.4–5.1 kyr (Katsuda et al. 2009; Allen et al. 2015, respectively), with distances of ∼700 pc (∼200 pc). A new relevance for this object came to light when HESS observations at TeV energies (HESS J10852–463; Aharonian et al. 2005, 2007; H.E.S.S. Collaboration et al. 2018) revealed that RX J0852.0–4622 is in fact a member of a class of gamma-ray SNRs that have a shell-type morphology resolved at gamma-ray energies. This reinforced the SNR’s status as a key object for the study of >TeV cosmic-ray (CR) acceleration, which was first suggested by the presence of TeV electron acceleration (Slane et al. 2001).

A key candidate production mechanism for the gamma-ray shell of RX J0852.0–4622 is neutral pion production via CR interactions with gas and subsequent pion decay (Aharonian et al. 2005, 2007; H.E.S.S. Collaboration et al. 2018). Indeed, Fermi-LAT GeV gamma-ray observations (Tanaka et al. 2011) reveal a spectrum that is compatible with CR acceleration, but current spectral studies cannot distinguish this scenario from one where the gamma-rays are generated by a high-energy electron population (H.E.S.S. Collaboration et al. 2018), even if the spectral model is fitted to a broad wavelength range (e.g., radio-continuum data from Stupar et al. 2005).

Since neutral pion production requires the interaction of CRs with gas, attempts to identify associated gas clouds may hold the key to understanding the nature of the RX J0852.0–4622. Recent work by Fukui et al. (2017) has successfully identified a void in atomic gas that has a near-perfect spatial match with RX J0852.0–4622, likely implying a core-collapse progenitor wind-blown bubble (see Section 3.3).

Slane et al. (2001) had previously noted that RX J0852.0–4622 was most likely a core-collapse event, although no compact object has been conclusively associated with RX J0852.0–4622. A coincident gamma-ray emitting pulsar wind nebula (PWN), PSR J0855–4644, was identified in the southeast (Acero et al. 2013), but it is believed to be unrelated despite having a compatible distance. A central X-ray source CXOU J085201.4–461753 at ∼1 kpc was investigated as an association (e.g., Kargaltsev et al. 2002). Reynoso et al. (2006) concluded that the object was likely unassociated with RX J0852.0–4622, instead favoring a planetary nebula counterpart for the compact object.

Molecular gas clumps pervade the SNR boundary (Fukui et al. 2017) in a scenario where the progenitor star is argued to be associated with evaporating gaseous globules, and mirroring the molecular clumps of sister SNR RX J1713.7–3946, which are well studied in literature (e.g., Fukui et al. 2003, 2012; Sano et al. 2010; Maxted et al. 2012, 2013). Fukui et al. (2017) find that the gamma-ray distribution traces the gas distribution, which is strong evidence for a significant hadronic gamma-ray component in the RX J0852.0–4622 gamma-ray emission.7

7 An alternative view is suggested by Sushch et al. (2018)—leptonic gamma-ray emission would also exhibit a gas–gamma-ray correlation if electron injection becomes more efficient in parts of the SNR shock moving through high gas densities. Regardless, the kinematic distance solution would likely remain valid independent of gamma-ray mechanism.
With the newly proposed RX J0852.0–4622 gas association, the time is right to test this scenario using new and archival multiwavelength data sets.

1.1. The Vela SNR

The Vela SNR is larger and overlaps RX J0852.0–4622, leading to alternate names for RX J0852.0–4622—Vela Jr. and Vela Z (in addition to G266.2–1.2). The PWN PSR J0855–4644 emits at TeV energies, but the Vela SNR itself has not been detected in HESS gamma-ray images. It follows that the Vela SNR is not an object considered for the study of >TeV CR acceleration. Nevertheless, the SNR may create some radio-continuum structures within the RX J0852.0–4622 shell that may cause confusion.

The Vela SNR is foreground to Vela Jr. at a distance of ~250–350 pc (e.g., Dubner et al. 1998; Cha et al. 1999; Caraveo et al. 2001). The best distance estimate probably comes from parallax measurements of the associated central compact object, the Vela pulsar, at 287±17 pc (Dodson et al. 2003). The corresponding spin-down age (Reichley et al. 1970) of 11.4 kyr is in agreement with the age of 18 ± 9 kyr, derived from the angular separation between the Vela pulsar and the Vela SNR centroid (as indicated by “explosion fragments”) given its measured proper motion (Aschenbach et al. 1995).

Sushch et al. (2011) proposed that the evolution of the Vela SNR took place inside the wind-blown bubble of the Wolf-Rayet star, γ Velorum. The model put the Vela SNR at the east–northeastern side of the bubble, with interactions taking place on the foreground side of the bubble. The resulting density difference between the shock component expanding into the bubble and the shock component expanding into the stellar bubble boundary might account for the asymmetry of the Vela SNR shell (Sushch et al. 2011; Sushch & Hnatyk 2014). Kim et al. (2012) found this model to be consistent with the discovery of FUV filaments along regions proposed to have a higher density. The authors also noted the possible first detection of Vela Jr. at FUV wavelengths through the examination of atomic line ratios (primarily OIII/OIv and OIII/CIV) that are more indicative of non-radiative shocks than other parts of the Vela SNR shell. The implication is that Vela Jr., which has non-radiative shocks, may be responsible for a component of oxygen ion emission seen by Miller (1973) or Nichols & Slavin (2004). This is despite low-ionization oxygen emission generally being associated with cooling in post-shocked gas associated with older radiative shocks.

While Vela Jr. generally exhibits shock speeds of ~3000 km s⁻¹ (Katsuda et al. 2009), the measured velocity of the foreground Vela SNR shock front ranges between ~100 and 280 km s⁻¹ (Cox 1972; Raymond et al. 1991; Jenkins & Wallerstein 1995; Bocchino et al. 1999, 2000; Cha & Sembach 2000; Pukhomonov et al. 2012), while so-called “explosion fragments” exhibit velocities of 660–1020 km s⁻¹ (Aschenbach et al. 1995; Sushch et al. 2011). Redman et al. (2000) find optical [S II] emission from one such fragment, RCW 37. The large associated speed and temperature lead the authors to suggest that Vela Jr. may be responsible for the fragment feature. This is in contrast to the majority of filamentary structures seen in optical atomic and ionic emission lines in the region. Emission lines such as [O III] have been attributed to the cooling of low-density shock-heated regions associated with shock speeds of ~100 km s⁻¹ in the Vela SNR (e.g., Raymond et al. 1997; Sankrit et al. 2003). UV emission of higher transition emission lines are attributed to faster components (150–170 km s⁻¹) within the Vela SNR shock (e.g., Raymond et al. 1981; Sankrit et al. 2003; Nichols & Slavin 2004; Slavin et al. 2004; Kim et al. 2012).

1.2. An Expanded History of RX J0852.0–4622

First imaged in X-rays by the ROSAT all-sky survey, RX J0852.0–4622 (i.e., Vela Jr.) was initially apparent at E > 1.3 keV (Aschenbach 1998). Before this X-ray discovery there were no reports of a radio SNR coincident with RX J0852.0–4622; although many Vela and Galactic Plane surveys covered the area. Duncan et al. (1996) and Bock et al. (1998) surveyed the SNR region with both the Parkes radio telescope and the Molonglo Observatory Synthesis Telescope (MOST) at 2420 MHz and 843 MHz, respectively. Before this time, the Parkes–MIT–NRAO survey (Griffith & Wright 1993) covered the area containing RX J0852.0–4622 at 4850 MHz, and a candidate nonthermal source coinciding with the northeastern limb of RX J0852.0–4622 was identified at 408 MHz as long ago as 1968 (Milne 1968).

Combi et al. (1999) presented a reanalysis of 2420 MHz data and a low angular resolution (30') detection of Vela Jr. at 1420 MHz in light of its discovery overlapping the Vela SNR at keV wavelengths. The authors concluded that the overall spectral index is ~−0.3, which is flatter than expected for young SNRs (typically α ~ −0.7). Follow-up observations (Duncan & Green 2000) measured a spectral index (α = −0.4 ± 0.15) for RX J0852.0–4622 that is consistently flatter than similar-age SNRs in the Milky Way and Magellanic Clouds (Bozzetto et al. 2017).

Filipović et al. (2001) showed that the structure of RX J0852.0–4622 is shell-like (barrel-shaped/bilateral) with good correlation between radio-continuum, EUV, and ROSAT PSPC X-ray emission. The radio-continuum emission coinciding with X-rays confirmed that synchrotron radiation is responsible for the north brightened X-ray limb (Bamba et al. 2005; Pannuti et al. 2010).

Stupar et al. (2005) presented a multifrequency radio-continuum study of RX J0852.0–4622 based on low-resolution mosaic observations with the Australia Telescope Compact Array (ATCA) radio interferometer at 1384 and 2496 MHz, Parkes 4850 MHz, and MOST 843 MHz survey data. They determined the radio spectral index for several prominent features of this SNR and found a sudden spectral turnover at 1384 MHz, but based on a closer inspection of the data leading to this turnover feature, we argue that observational shortcomings put the existence of this feature in doubt. This is due to the lack of short spacings within the array configuration used. In response to this, as part of this investigation we present new spectral index data toward RX J0852.0–4622.

We conduct a morphological investigation using radio-continuum data (including radio spectral index), H I, CO, Hα, [S II], [O III], UV, X-ray, and gamma-ray emission. We attempt to attribute components within the RX J0852.0–4622 field of view to either RX J0852.0–4622 (i.e., Vela Jr.) or the overlapping Vela SNR.

8 We note that such emission is also characteristic of the similar-speed shocks of Herbig–Haro objects (e.g., Schwartz 1978; Hartigan et al. 1987).

9 Where S ~ ν^α.
2. Observational Data

Various observations have been carried out on RX J0852.0–4622 over a period of 15 years. According to the literature, RX J0852.0–4622 is centered at R.A.(J2000) = 8°52′3″ and decl. (J2000) = −46°22′ (Aschenbach 1998), which is within the bounds of the larger Vela SNR. In this study, we highlight the GHz radio-continuum, optical emission line, and ultraviolet (UV) data.

2.1. ATCA Radio Continuum

The ATCA is an array of six 23 m dishes in Narrabri, New South Wales in Australia. The observations that were analyzed in this study were obtained from the ATNF online archive—ATOA. A list containing the observations that were analyzed, which span the frequency range between 1384 and 2868 MHz, are displayed in Table 1.

ATCA data from 1999 were taken as part of the Southern Galactic Plane Survey (SGPS; McClure-Griffiths et al. 2005) and had full coverage of the the RX J0852.0–4622 shell, while more recent measurements from 2011 were from a campaign targeting H I emission in the southwest of the SNR (Fukui et al. 2017). The latter observations were comprised of 430 points taken in mosaic mode and arranged in a hexagonal grid that covers approximately half of the SNR. The introduction of the Compact Array Broadband Backend system (CABB; Wilson et al. 2011) to ATCA provided a factor of 16 increase in the observing bandwidth compared to earlier observations of RX J0852.0–4622 (Stupar et al. 2005; Panotti et al. 2010). From 2 × 128 to 2 × 2048 MHz IF bands, the addition of 16 zoom windows significantly improved the rms noise and therefore detections of features of this SNR. With the added bandwidth and functionality from the inclusion of CABB, separate spectral line observations can be made using CABBs zoom band mode. This allowed for observations of both continuum and spectral lines simultaneously from 2011 onward. These data were taken with an increased image size for each pointing, facilitating effective image cleaning techniques (e.g., “Peeling,” as described in Hughes et al. 2006; Crawford et al. 2011).

The properties of each image examined in this analysis can be found in Table 2. Figure 1 indicates the coverage of the 1999 and 2011 ATCA observation campaigns. Images were processed using the MIRIAD software package (Sault et al. 1995). Frequencies range between 1332 and 2868 MHz, and typical rms noise levels are ∼1 mJy beam−1.

Figure 2 shows a final a noise-weighted combination of the 1999 and 2011 ATCA radio-continuum data sets (project codes C789 and C2449) spanning frequency bands between 1332 and 2868 MHz. The image largely replicates features observed in images by Stupar et al. (2005) and was produced to encapsulate the morphological features seen in individual images. The very bright, radio-loud H II region outside of the Vela Jr. field, RCW 38, produced large side lobes, so image boundaries were cropped prior to merging and data sets were normalized to ensure that morphological features were continuous. The final image, which encompasses ∼320° of the azimuthal angle of the SNR radio shell, is displayed in Figure 2. This image has limitations in coverage in the southeast and in the interpretation of flux, but can clearly illustrate filaments discussed in Section 3.2, so is ideal for morphological studies.

In addition to intensity images, we also present a radio spectral index map of RX J0852.0–4622 in Figure 3. The 1999 and 2011 data were examined independently, but only the 2011 results are displayed. The array configuration used to take the 1999 data lacked short spacings and systematic effects were introduced into the corresponding spectral index map.

2.2. Optical Data

This study utilizes measurements from the Australia National University 16 inch Boller & Chivens Telescope in 1999 February (Filipović et al. 2001). Filters targeted the doublet [O III], Hα and doublet [S II] transitions at 4861.3/5006.9, 6562.8 and 6718.3/6732.7 Å, respectively, over an exposure time of 600 s. We display [O III] emission in Figure 4.

2.3. UV Data

The 58–174 Å UV images from the Extreme-Ultraviolet Explorer (EUV; Welsh 1990) are displayed in Figure 5. UV data were collected using two Wolter-Schwarzschild Type I grazing incidence mirrors with a microchannel plate detector. The average exposure across the Galaxy is generally greater than 500 s.

The data were taken between 1991 and 1993 (Edelstein et al. 1993) and were utilized in previous studies by Filipović et al. (2001). The data have a natural angular resolution of ∼6 × 6′ and were smoothed to ∼10′ resolution.

2.4. Spectral CO and H I Data

Fukui et al. (2017) presented an analysis of the interstellar medium toward RX J0852.0–4622 with a focus on H I emission and molecular clumps traced by CO(1–0). The authors identified a candidate interstellar medium association for RX J0852.0–4622 and their data are used in our multi-wavelength investigation.

As detailed in Fukui et al. (2017), 21 cm H I data were taken with ATCA (see Section 2.1) and the 64 m Parkes telescope. The resultant combined data set has a beam FWHM of 245″ × 130″. CO(1–0) data at 115.290 GHz were taken with the Nanten telescope with a beam FWHM of 160″.

3. Results and Discussion

Like in radio-continuum images by Stupar et al. (2005), in Figure 2, the circular structure can be clearly discerned in the north and northwest of the RX J0852.0–4622 shell, in addition to the southern section. This RX J0852.0–4622 (Vela Jr.)

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Table 1: Summary of the ATCA Project File Radio-continuum Observations of RX J0852.0–4622 Used in This Study

| Project Code | Dates       | Array     | ν (MHz) | Bandwidth (MHz) | Channels |
|--------------|-------------|-----------|---------|-----------------|----------|
| C789         | 1999 Nov 14–15 | 210       | 2496   | 128             | 33       |
| C2449        | 2011 Feb 26–27 | EW352     | 2100   | 2048            | 2049     |
| C2449        | 2011 Mar 29–30 | EW367     | 2100   | 2048            | 2049     |

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10 http://atoa.atnf.csiro.au/
11 http://www.atnf.csiro.au/computing/software/miriad/
12 http://rsaa.anu.edu.au/observatories/telescopes/anu-16-inch-boller-chivens-telescope
13 https://heasarc.gsfc.nasa.gov/docs/euve/euve.html
Table 2
Summary of Various Image Properties of RX J0852.0–4622 Used in This Study

| Project Code | Frequency (MHz) | Bandwidth (MHz) | Pixel Size (arcsec) | Beam Size (arcsec) | Position Angle (degrees) | rms (mJy beam$^{-1}$) |
|--------------|-----------------|-----------------|---------------------|-------------------|-------------------------|---------------------|
| C789         | 1384            | 128             | 51.4                | 247.6 × 179.4     | 60.4                    | 1.5                 |
| C789         | 2296            | 128             | 28.9                | 118.8 × 89.0      | 55.4                    | 1.0                 |
| C2449        | 1332            | 512             | 27.2                | 120.4 × 99.0      | 7.3                     | 1.0                 |
| C2449        | 2100            | 2048            | 14.1                | 80.8 × 69.0       | 7.7                     | 0.4                 |
| C789         | 1844            | 512             | 20.3                | 91.6 × 77.4       | 1.9                     | 1.0                 |
| C789         | 2100            | 512             | 16.3                | 71.9 × 61.5       | 10.9                    | 1.0                 |
| C789         | 2100            | 512             | 14.1                | 59.5 × 50.0       | 8.7                     | 1.0                 |

The center position, SNR radius, and shell width were free parameters in the fit. The best-fit parameters are displayed in Table 3.

The optimum two-dimensional shell fit to the radio continuum suggests a center of $(\alpha, \delta) J2000 = (133^\circ30' -0.007^\circ, -46.34^\circ ±0.003^\circ)$ $(8''52''m 19'12, -46'20'24'0)$, and a radius of $3242^\prime_{35} -35$ arcsec ($\sim0.9^\circ$). We do not have sufficient coverage in the southeast of the SNR to warrant attempting an egg-shaped functional fit as suggested by X-ray emission studies (e.g., Aschenbach 1998; Fukui et al. 2017).

The $\sim10$ arcsec-scale errors associated with the SNR radius and the differing coverage of the 1999 and 2011 observations (see Figure 1) make the data unsuitable for expansion rate studies, particularly because previous X-ray expansion rate measurements (Katsuda et al. 2009; Allen et al. 2015) suggest that subarcsecond yr$^{-1}$ precision is required for this purpose.

3.2. Filamentary Features

We have identified filamentary structures within the 1999 and 2011 ATCA data sets that are not aligned with the circular RX J0852.0–4622 shell. We highlight these with dashed lines in Figure 2. These features are also indicated in Figure 4, which displays [O III] emission, and Figure 5, which displays short-wavelength UV emission. We note that none of the identified filaments correspond to the TeV gamma-ray emission or hard X-ray emission from the RX J0852.0–4622 shell. The unassociated PWN PSR J0855–4644 is also indicated in Figure 2. Coincident gamma-ray emission at this location is associated (Acero et al. 2013) with PWN PSR J0855–4644, not RX J0852.0–4622.

Filament A is a vertical filament of emission at R.A. $\sim134^\circ$ that partially overlaps with the northeastern edge of RX J0852.0–4622. This feature has previously been identified as “feature C” by Combi et al. (1999). Filament B is a $\sim17^\prime$-length radio-continuum structure centered at approximately $133.73^\circ$, $-46.25^\circ$. Filament C is a prominent feature of the 1999 and 2011 radio-continuum maps that extends almost vertically along R.A. $\sim132.5^\circ$ for a length of $\sim1.5''$ inside the perimeter of the RX J0852.0–4622 shell. Filament D is a half-arcminute-long filament feature, centered on approximately $133.45^\circ$, $-46.62^\circ$, at an angle of $\sim24$° to the ecliptic plane.

3.2.1. High Energy Correspondence

The broadband X-ray structure in the top right panel of Figure 2 is dominated by thermal emission from the Vela SNR (Aschenbach et al. 1995; Aschenbach 1998). This means that the broadband X-ray structure can help to distinguish the radio-continuum structure of the Vela SNR versus Vela Jr., allowing us to investigate the origin of filaments A, B, C, and D.
Similarly, UV emission in Figure 5 highlights the older, foreground Vela SNR with perhaps a smaller contamination from the Vela Jr. shocks due to the larger distance of Vela Jr.

Referring to Figures 2 and 5, filaments A, C, and D have corresponding soft X-ray and UV emission. Since this emission is believed to be dominated by thermal emission from the Vela SNR, Filaments A, C, and D have clear thermal counterparts, strongly suggesting an association with the Vela SNR. Furthermore, UV and soft X-ray emission toward filament A appear to extend northward beyond the RX J0852.0–4622 perimeter, toward more vertical features that are likely associated with the Vela SNR (see Figures 2, 4, and 5). Conversely, all filaments, A, B, C, and D, do not have clear correspondences with hard X-rays or gamma-ray emission, suggesting no association with RX J0852.0–4622.

Filament B does not have any UV, X-ray, or gamma-ray counterpart, so we are unable to favor either a Vela SNR or Vela Jr. origin for this feature.

3.2.2. Optical Correspondence

[O III] emission is considered a good tracer of cooling post-shock gas associated with radiative-phase SNRs, consistent with emission from the Vela SNR. In Figure 4, the structure of the Vela SNR can be seen to overlap and align well with filaments A and D. These have corresponding filamentary [O III] emission structure, as seen in Figure 7, which shows [O III] with [S II] and Hα emission. Both filaments B and C have no optical counterpart.

The eastern side of the filament D radio-continuum emission is coincident with an arc in [O III] emission (Figure 7). This feature, which we have coined the “Vela Claw,” may be related to a shock interaction with gas and is discussed in Section 3.3. Generally, a lack of [O III] emission toward the outer circular shell of RX J0852.0–4622 suggests that [O III] does not generally trace the fast \( \sim 10^3 \) km s\(^{-1}\) RX J0852.0–4622 shocks, consistent with expectations.
Figure 3. Spectral index derived from project C2449 (year 2011) toward the northwestern rim of RX J0852.0–4622 (Vela Jr.). Black, dashed radio-continuum contours from a single frequency band are overlaid. Blue 2, 4, 6, 8, 10, and 12 K km s\(^{-1}\) Nanten \(^{12}\)CO(1-0) integrated emission (28–33 km s\(^{-1}\)) contours are also overlaid (as seen in Figure 1 of Fukui et al. 2017). The estimated uncertainty in spectral index is \(\sim 15\%–20\%\).

Figure 4. Two-color image of the 500 nm [O III] emission image (Filipović et al. 2001) in blue and ATCA 1332–2868 MHz radio-continuum emission in red. The approximate location of the Vela SNR is indicated by a dashed green circle. In the right panel, yellow dashed lines, labeled A–D, indicate filamentary structures.

Figure 5. Three-color image featuring 58–174 Å ultraviolet emission from the EUVE satellite (red), and gas tracers at the velocity of a void. ATCA and Parkes H I emission integrated between 22 and 33 km s\(^{-1}\) is green, with dashed green contour levels of 150, 200, 250, and 300 K km s\(^{-1}\) displayed (as seen in Figure 1 of Fukui et al. 2017). Nanten \(^{12}\)CO(1-0) emission integrated between 28 and 33 km s\(^{-1}\) is blue in the image, with blue 2, 4, 6, 8, 10, and 12 K km s\(^{-1}\) contours overlaid (as seen in Figure 1 of Fukui et al. 2017).
## Table 3
Results of a χ²-minimization Fit of a Two-dimensional Shell Function to Radio-continuum Data

| Year | Central Frequency (MHz) | R.A. | Decl. | Radius a | Width |
|------|-------------------------|------|-------|----------|-------|
|      |                         | (deg) | (deg) | (arcsec) | (arcsec) |
| 1999 | 1384                    | 132.98 ±0.001 | -46.26 ±0.001 | 2943 ±12 | 50 ±13 |
|      | 2496                    | 132.99 ±0.003 | -46.27 ±0.003 | 2965 ±17 | 125 ±7 |
| 2011 | 1332                    | 133.19 ±0.008 | -46.29 ±0.010 | 3380 ±40 | 185 ±12 |
|      | 1844                    | 133.22 ±0.010 | -46.27 ±0.007 | 3433 ±44 | 160 ±22 |
|      | 2100                    | 133.19 ±0.009 | -46.28 ±0.008 | 3377 ±46 | 157 ±36 |
|      | 2356                    | 133.23 ±0.014 | -46.26 ±0.015 | 3471 ±50 | 152 ±46 |
|      | 2868                    | 133.23 ±0.013 | -46.26 ±0.009 | 3456 ±73 | 127 ±39 |
| 1999 + 2011 | 1332–2868 | 133.08 ±0.007 | -46.34 ±0.005 | 3242 ±34 | -b |

Notes. Central position (J2000 R.A., decl.), radius, and width were solved for each radio-continuum image. The displayed width has been deconvolved assuming a beam FWHM that is the average of the minor and major axis of the beam FWHM (see Table 2).

a The radius displayed is the inner shell radius derived from the SHERPA fit plus half of the non-deconvolved shell width.

b The deconvolved shell width is not calculated because the beam FWHM is unclear for this merged data, but a non-deconvolved width of 310±13 arcsec is found.

Figure 6. Three-color image featuring radio continuum (red; also in Figure 2), and gas tracers at the velocity of a void. ATCA and Parkes H I emission integrated between 22 and 33 km s⁻¹ is green, with dashed green contour levels of 150, 200, and 250 K km s⁻¹ displayed (as seen in Figure 1 of Fukui et al. 2017). Nanten ¹²CO(1-0) emission integrated between 28 and 33 km s⁻¹ is blue, with blue 2, 4, 6, 8, 10, and 12 K km s⁻¹ contours overlaid (as seen in Figure 1 of Fukui et al. 2017).

### 3.3. Correspondence with the Interstellar Medium Associated with RX J0852.0–4622

Figure 6 shows the ATCA radio-continuum morphology against a backdrop of a H I dip identified by Fukui et al. (2017) to be likely associated with RX J0852.0–4622. The SNR shell corresponds well to this dip in H I emission (velocity ~30 km s⁻¹), with the eastern side partially overlapping the contours of atomic gas, while regions of the northeast and south sit outside the lowest H I contour level within the H I dip. It follows that ATCA radio-continuum emission supports the gas association found by Fukui et al. (2017).

On examination of the [O III]-traced filament D, a forking structure was identified: we denote this feature as the Vela Claw and indicate its position and morphology in Figure 7. The Claw appears to be part of a larger structure that is connected to the [O III] emission coincident with filament D. The [O III] filament diverges into two filamentary structures to form a claw-like structure. This appears to occur at a location near a stripped CO clump referred to as “CO30E” by Fukui et al. (2017), which the authors suggested to be associated with Vela Jr. The diverging filament forms a crescent around clump CO30E from the northwest to the east, suggesting that the [O III] emission may be associated with the Vela Jr. shock.

Two scenarios are considered to explain the origin of the Vela Claw: (i) Vela Jr. generating the Vela Claw, and (ii) the Vela SNR generating the Vela Claw.

Scenario (ii) is consistent with the accepted picture of how optical [O III] emission is produced from SNRs, i.e., the radiative cooling of diffuse gas in the wake of a ~100 km s⁻¹ shockwave (see Section 1.1). Furthermore, the Vela SNR is a known emitter of this transition, as is clearly seen extensively throughout the Vela SNR shell (see Figure 4). It follows that if scenario (ii) is correct, the Vela Claw correspondence with clump CO30E might simply be coincidental. Indeed, this scenario is consistent with the Vela Claw being associated with the coincident radio-continuum feature, filament D, for which a Vela SNR origin is perhaps favored by the remarkable UV/soft X-ray structure attributable to the Vela SNR (see Section 3.2.1). Alternatively, the correspondence might be evidence for an association of clump CO30E with the Vela SNR—a scenario that is disfavored by the remarkable correlation between gas near the CO30E Galactic velocity and the Vela Jr. gamma-ray emission (Fukui et al. 2017), assuming that Vela Jr. and the Vela SNR are indeed at different distances (~750 and ~300 pc, respectively), as currently believed.

Scenario (i), an association of the Vela Claw with Vela Jr., would be a surprising result because the conditions within the ~3000 km s⁻¹ Vela Jr. shock are not considered conducive to stimulate optical [O III] emission, or indeed any significant detectable thermal cooling lines at other wavelengths. Naively, an association of Vela Jr. with clump CO30E and the Vela Claw might require that the SNR shock (forward or reverse) is slowed significantly by the clump CO30E density gradient. If we assume a constant ram-pressure model, \( P = \rho v^2 \), where \( \rho \) is the gas density and \( v \) is the shock speed, the...
Sutherland & Dopita (1995) proposed another mechanism to explain thermal emission from seven young SNRs (including Cassiopeia A, SNR G292.0+1.8, and Puppis A) that may also be able to describe scenario (i) in Vela Jr. In the Sutherland & Dopita (1995) model, knots of oxygen-rich ejecta material move through a low-density medium until encountering a density discontinuity at a relative velocity of several $\times 1000$ km$^{-1}$. A density increase of $100\times$ is said to translate to internal cloud shock speeds of $\sim 100$ km s$^{-1}$, which could lead to the observed [O III] emission.

The validity of scenario (i) is complicated by the expectation that a thermal UV/X-ray emission counterpart to the [O III] emission might be expected, as is the case for shell segments of the SNR RCW 86, which exhibits shock velocities that vary by an order of magnitude due to sharp localized density gradients (e.g., Vink et al. 2006; Broersen et al. 2014). As discussed in Section 3.2.1, the Vela SNR likely dominates the thermal UV/X-ray emission in this region; therefore, scenario (i) is difficult to test with UV or X-ray data. Figure 7 (bottom) shows the significant overlap between the Vela Claw and ROSAT soft thermal X-ray emission. Small-scale spectral studies of the X-ray emission might help to distinguish a thermal emission component from Vela Jr. toward the Vela Claw. Such a detection would not only strengthen the association between the SNR and clump CO30E, but would be further model-dependent evidence of the core-collapse nature of the progenitor event, since the Sutherland & Dopita (1995) model requires oxygen-rich ejecta material inherent to core-collapse events.

Also displayed in Figure 6 are CO-traced molecular gas clumps at the outskirts of the HI dip. Toward the northwest region of RX J0852.0–4622 the signal-to-noise level and resolution of the 2011 ATCA data set were sufficient across the bands to derive a reliable spectral index map. In Figure 3, radio-continuum emission toward the rim of RX J0852.0–4622 may flatten ($\gtrsim 0.5$) toward a dense molecular region traced by CO(1-0) emission—a scenario indicative of an SNR–cloud shock interaction (e.g., Keohane et al. 1997; Ingallinera et al. 2014). No other suggestion of a shock–cloud interaction in this region is seen at other wavelengths, including thermal UV and X-ray emission.

4. Conclusion

We suggest that the 1332–2868 MHz radio-continuum emission of RX J0852.0–4622 is well characterized by a two-dimensional shell of $3242 \pm 35$ arcsec centered at (l, b) = ($133^\circ 08 \pm 0^\circ 01, -46^\circ 34 \pm 0^\circ 005$). Several filamentary structures are identified and multiwavelength data are examined to investigate their relation to RX J0852.0–4622.

Based only on morphological studies of radio-continuum, UV, X-ray, and gamma-ray emission, three radio filaments toward RX J0852.0–4622 show no indication of an RX J0852.0–4622 origin, while one filament has no clear multiwavelength counterpart. An investigation of [O III] emission, however, led to the identification of a feature we coined the Vela Claw, which is possibly associated with one of the radio filaments. The feature corresponds to a southeast molecular clump previously suggested to be stripped by the progenitor of RX J0852.0–4622 (Fukui et al. 2017). Although the [O III] feature is consistent with an origin in the shocks of the coincident Vela SNR, motivated by morphological correspondence with RX J0852.0–4622, we propose the possibility

Figure 7. Top: a three-color image featuring H$\alpha$ (red), [S II] (green), and [O III] (blue) from the Boller & Chivens Telescope. Red 150 and 200 K km s$^{-1}$ contours of ATCA and Parkes HI emission integrated between 22 and 33 km s$^{-1}$ are overlaid (as seen as Figure 1 of Fukui et al. 2017). Yellow 2, 4, 6, 8, 10, and 12 K km s$^{-1}$ contours of Nanten $^{12}$CO(1-0) emission integrated between 28 and 33 km s$^{-1}$ are also overlaid (as seen in Figure 1 of Fukui et al. 2017). Bottom: same as the top panel, only red HI contours have been replaced by magenta contours that indicate ROSAT broadband (0.2–2.4 keV) X-ray emission (Aschenbach 1998).

Vela Jr. shock might be slowed to $\sim 10\%$ of the initial speed in a localized region with a sharp density gradient of $\sim 100\times$. This is plausibly occurring for Vela Jr. Clump CO30E has a mass of 180 $M_\odot$ and an approximate radius of 3 pc (Table 1 of Fukui et al. 2017). Assuming a spherical geometry, the average H$_2$ density of clump CO30E is approximately $n \approx 30$ cm$^{-3}$, which would represent a $>100\times$ increase in density with respect to the density expected for a wind-blown cavity region (e.g., $\sim 0.1$ cm$^{-3}$), like that proposed for the evolution of Vela Jr. (Fukui et al. 2017).
of RX J0852.0–4622 triggering the [O III] emission of the Vela Claw. Proof of an association would reinforce the gas association found by Fukui et al. (2017).

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