The Peculiar Multiwavelength Evolution Of V1535 Sco

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Abstract

We present multiwavelength observations of the unusual nova V1535 Sco throughout its outburst in 2015. Early radio observations were consistent with synchrotron emission, and early X-ray observations revealed the presence of high-energy (>1 keV) photons. These indicated that strong shocks were present during the first ~2 weeks of the nova’s evolution. The radio spectral energy distribution was consistent with thermal emission from week 2 to week 6. Starting in week 7, the radio emission again showed evidence of synchrotron emission, and there was an increase in X-ray emission, indicating a second shock event. The optical spectra show evidence of at least two separate outflows, with the faster outflow possibly having a bipolar morphology. The optical and near-infrared light curves and the X-ray N_H measurements indicated that the companion star is likely a K giant.

Key words: novae, cataclysmic variables – radio continuum: stars – stars: individual (V1535 Sco) – white dwarfs – X-rays: stars

1. Introduction

A nova eruption occurs when a white dwarf has accreted enough material from a companion star to trigger thermonuclear runaway on its surface (e.g., Starrfield et al. 1972). Observations with modern telescopes have revealed the presence of strong shocks in nova systems. In particular, the discovery of GeV γ-rays from V407 Cyg indicated that in at least some systems the shocks were strong enough to accelerate particles to very high energies (Abdo et al. 2010). In the case of V407 Cyg, the shocks were the result of the nova ejecta colliding with a dense stellar wind from a Mira variable companion (Abdo et al. 2010). Much to the surprise of the nova community, further observations with the Fermi Gamma-ray Space Telescope discovered γ-ray emission from systems with main-sequence companions (e.g., Ackermann et al. 2014).

While observations across the electromagnetic spectrum have contributed to the discovery of shocks in novae, radio observations have proven to be particularly valuable. Resolved radio images can reveal nonspherical structure and provide evidence for multiple outflows, as in the case of V959 Mon (Chomiuk et al. 2014). Early monitoring of the radio emission, even when the ejecta are too small to resolve, has also proven to be an effective probe of shocks in novae. The shocks can manifest as synchrotron emission with nonthermal brightness temperatures, in spectacular ways as in V1723 Aql (Weston et al. 2016b), or in more subtle ways as in V5589 Sgr (Weston et al. 2016a). When the radio synchrotron emission is bright enough, the shocks can be directly imaged with very long baseline interferometry, as in V959 Mon (Chomiuk et al. 2014) and RS Oph (Rupen et al. 2008; Sokoloski et al. 2008).

Observations with modern X-ray telescopes (XRTs) have also proven to be useful in characterizing shocks in novae. Those novae embedded within the wind of a giant companion typically emit bright, hard X-rays early in their evolution, such as RS Oph (Bode et al. 2006; Nelson et al. 2008) and V745 Sco (Orio et al. 2015; Page et al. 2015). Novae in systems with main-sequence companions are also capable of producing strong X-rays, but typically later in their evolution. Such was the case in both V382 Vel (Mukai & Ishida 2001) and V5589 Sgr (Weston et al. 2016a).

On 2015 February 11, the nova V1535 Sco was discovered in the constellation Scorpius. It was reported in vsnet-alert 18276 by P. Schmeer and in CBET 4078 by T. Kojina. Early optical and near-infrared follow-up indicated that the nova was fading rapidly (Walter 2015). The combination of rapid fading and a possible bright near-infrared counterpart indicated that the companion star could be an M giant, in which case the nova could be embedded in the wind from a giant companion (Walter 2015). Srivastava et al. (2015) later argued that the companion could be a K giant based on pre-eruption Two Micron All Sky Survey (2MASS) photometry of a likely counterpart (2MASS J17032617-3504178). Spectroscopic observations indicated that it was an He/N-type nova (Srivastava et al. 2015; Walter 2015). Early X-ray and radio observations (Linford et al. 2015; Nelson et al. 2015) indicated the presence of strong shocks in the ejecta, which was further evidence that the ejecta were expanding into a dense medium. The nova was originally given the designation PNV J1703260-3504140, then known as
Nova Sco 2015, and eventually given the official designation V1535 Sco. Srivastava et al. (2015) also noted that narrowing of the H-line profiles in the infrared indicated the presence of a deceleration shock and estimated the total mass ejected to be between $4.5 \times 10^{-6}$ and $2.6 \times 10^{-4} \, \epsilon \, M_\odot$ (where $\epsilon$ is the filling factor of the ejecta).

During the 2015 outburst, no Fermi Gamma-ray Space Telescope staring mode observations were scheduled, and the nova was not reported as a detection from the survey mode data. However, it must be noted that Fermi is generally less sensitive to transients at the Galactic center, due to a combination of the high background and the north–south “rocking” profile of the survey mode results in the Galactic center having minimal exposure (Acero et al. 2015). It is therefore possible that V1535 Sco produced $\gamma$-rays like other novae (e.g., V407 Cyg and V745 Sco; Abdo et al. 2010; Cheung et al. 2014), but none were detectable owing to these limiting factors. Recent work by Morris et al. (2017) argues that all novae produce $\gamma$-ray emission, but we mainly detect the nearby ones with Fermi.

In this paper, we present our multiwavelength observations of V1535 Sco made during 2015. These observations were made with the Karl J. Jansky Very Large Array (VLA), the Very Long Baseline Array (VLBA), the Swift XRT, and the Small & Moderate Aperture Research Telescope System (SMARTS). We present our observations and data reduction methods in Section 2. Our knowledge about the distance to V1535 Sco is discussed in Section 3. In Section 4, we present results from the multiwavelength observations. We discuss our findings in Section 5. Final conclusions are summarized in Section 6. Throughout this paper, we use the initial optical detection of the nova on 2015 February 11.837 (MJD 57,064.837) as day 0.0. We also use the term “embedded nova” to refer to any nova embedded in the wind material from its companion star (e.g., Chomiuk et al. 2012; Mukai et al. 2014).

2. Observations and Data Reduction

2.1. VLA Observations

We began monitoring V1535 Sco with the VLA within 64 hr of its discovery in the optical. The first epoch only included observations at C band (4.0–8.0 GHz) and Ka band (26.5–40.0 GHz). All following epochs also included observations at L band (1.0–2.0 GHz) and Ku band (12.0–18.0 GHz). To maximize spectral coverage, all bands were split into upper and lower sidebands. For the first eight epochs, we used 8-bit sampling for all frequencies. This gave us a total bandwidth of 1.0 GHz at L band and 2.0 GHz at all other bands. For the ninth epoch (day 93.463) we used 3-bit sampling for Ku band and Ka band, resulting in total bandwidths of 6.0 and 8.0 GHz, respectively. For the final epoch (day 122.363), we used 3-bit sampling for C band, Ku band, and Ka band, giving total bandwidths of 4.0, 6.0, and 8.0 GHz, respectively. Ten epochs were observed under the program VLA/13B-057, and one epoch (day 93.463) was observed under the program S61420. The nova was detected during the first epoch (day 2.7) and remained detectable at multiple frequencies for nearly 100 days. We ceased observations once the nova had faded to the point where it was no longer detected at all frequencies.

For all epochs, we used the absolute flux calibrator 3C 286. Complex gains calibrators were J1626-2951 for both L band and C band and J1650-2943 for both Ku band and Ka band. All VLA data were calibrated with the NRAO VLA calibration pipeline, version 1.3.1, which uses CASA\textsuperscript{12} version 4.2.2. The pipeline script was executed on either a dedicated desktop or an NRAO Lustre node. Once calibrated, the data were exported to AIPS\textsuperscript{13} for additional flagging. The fully flagged data were imaged with Difmap (Shepherd 1997). The images were then imported back into AIPS, and flux densities were measured using the task JMFIT. The L-band and C-band data from 2015 April 18 were also calibrated in AIPS in order to look for polarization. Also, the Ku-band and Ka-band data from 2015 March 25 were recalibrated in AIPS to check the results of the CASA pipeline. Our VLA results are presented in Table 1. For nondetections, we calculated the upper limit as the flux density at the nova location plus 3 times the image rms. Our uncertainties are calculated by adding the image rms and an absolute flux density uncertainty in quadrature. Perley & Butler (2013) report that the VLA absolute flux density quality is stable to within 1% for 1–20 GHz and within 3% for 20–50 GHz. Because V1535 Sco is far from 3C 286, our uncertainty in the flux density calibration will be higher. We adopt an absolute flux density uncertainty of 3% for 1–20 GHz and 5% for above 20 GHz.

2.2. VLBA Observations

We had two epochs of VLBA observations under the program VLBA/15A-269, both in C band with a central frequency of 4.87 GHz and a total bandwidth of 256 MHz. For both epochs, we used J1709-3525 as the phase reference source. The bright sources J1656-3302 and J1713-3418 were also observed as a means of gauging the successful calibration of the nova. For the first epoch, three antennas were not usable: Hancock, North Liberty, and Maunakea. For the second epoch, Hancock and Maunakea could again not be used. The total time on source for each epoch was approximately 177.3 minutes (or 2.96 hr).

Both epochs were calibrated using standard routines in AIPS, including the new bandpass correction routine described by Walker (2014). Images were made in Difmap. The nova was detected in the first epoch, but not in the second epoch (see Table 2). Schedules for further epochs were submitted, but conflict with a top-priority VLBA program prevented them from being observed. The position of the compact source detected in the first VLBA epoch was R.A. 17°03′26″:17218 ± 0′00002, decl. −35°04′17″:87267 ± 0′00071.

2.3. Swift Observations

We obtained 14 epochs of Swift XRT observations. The exposure times ranged from 2.5 to 4.9 ks. The nova was detected by the XRT in 11 of the 14 observations. Details of the observations are given in Table 3.

We divided the Swift XRT detections into soft and hard bands based on the photon energy, $E$. We chose $E < 1.0$ keV to be soft and $E > 1.0$ keV to be hard. Our decision to use these designations is based on previous observations of

\textsuperscript{12} https://casa.nrao.edu/

\textsuperscript{13} http://www.aips.nrao.edu
| UT Date   | Day  | VLA Config. | Central Frequency (GHz) | Time on Source (minutes) | Flux Density (mJy) | Uncertainty (mJy) |
|-----------|------|-------------|-------------------------|--------------------------|-------------------|------------------|
| 2015 Feb 14 | 2.663 | B           | 4.55                    | 13.6                     | 4.13              | 0.13             |
|           |      |             | 7.38                    | 13.6                     | 2.786             | 0.085            |
|           |      |             | 28.2                    | 11.3                     | 0.819             | 0.071            |
|           |      |             | 36.5                    | 11.3                     | 0.675             | 0.090            |
| 2015 Feb 18 | 6.663 | B           | 13.5                    | 11.9                     | 0.416             | 0.021            |
|           |      |             | 17.4                    | 11.9                     | 0.344             | 0.024            |
|           |      |             | 28.2                    | 11.8                     | 0.295             | 0.053            |
|           |      |             | 36.5                    | 11.8                     | 0.376             | 0.074            |
| 2015 Feb 19 | 7.663 | B           | 1.26                    | 15.6                     | 1.57              | 0.090            |
|           |      |             | 1.74                    | 15.6                     | 1.21              | 0.081            |
|           |      |             | 4.55                    | 13.6                     | 0.650             | 0.026            |
|           |      |             | 7.38                    | 13.6                     | 0.439             | 0.018            |
| 2015 Feb 24 | 12.763 | B          | 13.5                    | 12.5                     | 0.385             | 0.020            |
|           |      |             | 17.4                    | 12.5                     | 0.456             | 0.024            |
|           |      |             | 28.2                    | 12.4                     | 0.785             | 0.062            |
|           |      |             | 36.5                    | 12.4                     | 0.845             | 0.087            |
| 2015 Mar 01 | 17.663 | B          | 1.26                    | 15.6                     | <0.317            | 0.10             |
|           |      |             | 1.74                    | 15.6                     | <0.317            | 0.066            |
|           |      |             | 4.55                    | 13.6                     | 0.221             | 0.019            |
|           |      |             | 7.38                    | 13.6                     | 0.192             | 0.017            |
| 2015 Mar 07 | 23.663 | B          | 13.5                    | 12.0                     | 0.585             | 0.024            |
|           |      |             | 17.4                    | 12.0                     | 0.755             | 0.031            |
|           |      |             | 28.2                    | 11.9                     | 1.15              | 0.074            |
|           |      |             | 36.5                    | 11.9                     | 1.68              | 0.11             |
| 2015 Mar 10 | 26.563 | B          | 1.26                    | 15.6                     | <0.374            | 0.074            |
|           |      |             | 1.74                    | 15.6                     | <0.271            | 0.054            |
|           |      |             | 4.55                    | 13.5                     | 0.455             | 0.023            |
|           |      |             | 7.38                    | 13.5                     | 0.536             | 0.021            |
| 2015 Mar 25 | 41.583 | B          | 13.5                    | 12.0                     | 0.267             | 0.015            |
|           |      |             | 17.4                    | 12.0                     | 0.299             | 0.017            |
|           |      |             | 28.2                    | 12.0                     | 0.348             | 0.044            |
|           |      |             | 36.5                    | 12.0                     | <0.351            | 0.055            |
| 2015 Mar 25 | 41.633 | B          | 1.26                    | 15.6                     | <0.609            | 0.112            |
|           |      |             | 1.74                    | 15.6                     | <0.271            | 0.060            |
|           |      |             | 4.55                    | 13.8                     | 0.222             | 0.017            |
|           |      |             | 7.38                    | 13.8                     | 0.253             | 0.014            |
| 2015 Apr 07 | 54.563 | B          | 13.5                    | 12.5                     | 0.457             | 0.028            |
|           |      |             | 17.4                    | 12.5                     | 0.399             | 0.022            |
|           |      |             | 28.2                    | 12.4                     | 0.323             | 0.047            |
|           |      |             | 36.5                    | 12.4                     | 0.276             | 0.062            |
| 2015 Apr 08 | 55.733 | B          | 1.26                    | 15.7                     | 0.87              | 0.10             |
|           |      |             | 1.74                    | 15.7                     | 0.661             | 0.060            |
|           |      |             | 4.55                    | 13.7                     | 0.483             | 0.024            |
|           |      |             | 7.38                    | 13.7                     | 0.374             | 0.018            |
| 2015 Apr 18 | 65.513 | B          | 1.26                    | 16.6                     | 0.444             | 0.082            |
|           |      |             | 1.74                    | 16.6                     | 0.258             | 0.057            |
|           |      |             | 4.55                    | 14.6                     | 0.256             | 0.019            |
|           |      |             | 7.38                    | 14.6                     | 0.228             | 0.014            |
| 2015 Apr 19 | 66.493 | B          | 13.5                    | 12.0                     | 0.209             | 0.017            |
|           |      |             | 17.4                    | 12.0                     | 0.167             | 0.023            |
|           |      |             | 28.2                    | 12.0                     | 0.173             | 0.049            |
|           |      |             | 36.5                    | 12.0                     | <0.289            | 0.083            |
| 2015 May 01 | 78.463 | B          | 1.26                    | 15.6                     | <0.32             | 0.11             |
|           |      |             | 1.74                    | 15.6                     | <0.378            | 0.071            |
|           |      |             | 4.55                    | 13.6                     | 0.170             | 0.019            |
|           |      |             | 7.38                    | 13.6                     | 0.139             | 0.015            |
| 2015 May 01 | 78.503 | B          | 13.5                    | 12.1                     | 0.129             | 0.017            |
|           |      |             | 17.4                    | 12.1                     | 0.164             | 0.022            |
|           |      |             | 28.2                    | 12.0                     | 0.174             | 0.053            |
|           |      |             | 36.5                    | 12.0                     | <0.241            | 0.075            |
| 2015 May 16 | 93.463 | B → BnA    | 1.26                    | 8.0                      | <0.531            | 0.177            |
|           |      |             | 1.74                    | 8.0                      | <0.336            | 0.078            |
|           |      |             | 4.55                    | 8.0                      | 0.0727            | 0.023            |
novae that indicate that the $E < 1.0$ keV band can be dominated by the supersoft X-rays, while the $E > 1.0$ keV X-rays are likely to be from shocks (e.g., Mukai et al. 2008, 2014). The X-ray emission was initially hard. The soft emission increased over the first ~20 days, while the hard emission decreased over the same time period. We had no detections with the XRT after day 67. Our Swift XRT results are plotted in Figure 1.

### Table 1

(Continued)

| UT Date   | Day*  | VLA Config. | Central Frequency (GHz) | Time on Source (minutes) | Flux Density (mJy) | Uncertainty (mJy) |
|-----------|-------|-------------|-------------------------|-------------------------|-------------------|------------------|
| 2015 Jun 14 | 122.363 | BnA → A | 7.38 | 8.0 | 0.0708 | 0.017 |
|           |       |             | 13.5 | 8.0 | 0.0518 | 0.018 |
|           |       |             | 16.5 | 8.0 | <0.0859 | 0.021 |
|           |       |             | 29.5 | 9.0 | <0.149 | 0.036 |
|           |       |             | 35.0 | 9.0 | <0.135 | 0.045 |

Note. a We take the time of initial detection 2015 February 11.837 UT (MJD 57,064.837) to be day 0.0.

### Table 2

VLBA Observations

| UT Date   | Day*  | Central Frequency (GHz) | Time on Source (minutes) | Flux Density (mJy) | Uncertainty (mJy) |
|-----------|-------|-------------------------|-------------------------|-------------------|------------------|
| 2015 Feb 19 | 7.663 | 4.87 | 177.3 | 0.477 | 0.056 |
| 2015 Feb 24 | 12.763 | 4.87 | 177.3 | <0.278 | 0.041 |

Note. a We take the time of initial detection 2015 February 11.837 UT (MJD 57,064.837) to be day 0.0.

### Table 3

Swift/XRT Observations

| ObsID       | Day*  | Exposure (s) | Total Counts | 0.3–1.0 keV Count Rate | 1–10 keV Count Rate | Total Count Rate |
|-------------|-------|--------------|--------------|------------------------|---------------------|------------------|
| 00033634002 | 4.16  | 4084         | 591          | 0.0062                 | 0.1578              | 0.1640           |
| 00033634003 | 11.04 | 3485         | 198          | 0.0555                 | 0.0878              | 0.1428           |
| 00033634004 | 13.94 | 3407         | 431          | 0.0886                 | 0.0553              | 0.1429           |
| 00033634005 | 17.93 | 4669         | 676          | 0.1342                 | 0.0329              | 0.1666           |
| 00033634006 | 24.75 | 2959         | 252          | 0.0925                 | 0.0174              | 0.1091           |
| 00033634007 | 31.51 | 4378         | 46           | 0.0102                 | 0.0067              | 0.0161           |
| 00033634008 | 38.77 | 4568         | 27           | 0.0021                 | 0.0054              | 0.0075           |
| 00033634009 | 45.55 | 2138         | ...          | <0.0011                | <0.0011             | <0.0082          |
| 00033634010 | 49.08 | 2575         | 5            | 0.0008                 | 0.0021              | 0.0024           |
| 00033634011 | 53.07 | 4714         | 12           | 0.0016                 | 0.0025              | 0.0041           |
| 00033634012 | 60.03 | 4845         | 13           | 0.0013                 | 0.0015              | 0.0027           |
| 00033634013 | 66.71 | 2979         | 7            | 0.0007                 | 0.0026              | 0.0028           |
| 00033634014 | 73.86 | 4934         | ...          | <0.0005                | <0.0002             | <0.0036          |
| 00033634015 | 80.32 | 4526         | ...          | <0.0002                | <0.0001             | <0.0024          |

Note. a We take the time of initial detection 2015 February 11.837 UT (MJD 57,064.837) to be day 0.0.

2.4. SMARTS Photometric and Spectroscopic Observations

SMARTS monitors novae in the optical and near-infrared and provides the results to the public via the Stony Brook/SMARTS Spectroscopic Atlas of (mostly) Southern Novae.14 Photometric observations of V1535 Sco began on 2015

14 http://www.astro.sunysb.edu/fwalter/SMARTS/NovaAtlas/atlas.html
February 13.35 using the ANDICAM\textsuperscript{15} dual-channel imager on the SMARTS 1.3 m telescope.

Spectroscopic measurements of the ejecta began on 2015 February 13.5 as part of the SMARTS observation campaign using the CHIRON echelle spectrometer on the 1.5 m SMARTS telescope (Tokovinin et al. 2013). As an example, we show the spectrum from day 1.565 in Figure 2. There is P Cyg absorption present on the H\textbeta (4861 Å), H\gamma (4340 Å), He I (4471, 4921, and 5879 Å), Fe II (5169 Å), and O I (7774 and 8446 Å) lines. This is unusual for an He/N nova, as they typically do not have much mass loss.

The H\alpha line width measurements are presented in Table 4, and we show the evolution of the H\alpha line from day 1.565 to day 16.548 in Figure 3. Because we are concerned with the outermost edge of the main component of the ejecta, we estimate the maximum velocity as the full width at 3\sigma (FW3\sigma). We convert the H\alpha FWHM velocities to FW3\sigma velocities by assuming that the core of the spectral line has a Gaussian shape, and then we multiply by a factor of 1.5(2 ln 2)\textsuperscript{-1/2} in order to get the 3\sigma velocities. Our velocity evolution is shown in Figure 4. While the measured velocity of the ejecta appears to decrease with time, we must emphasize that what is actually being measured here is the velocity of the H\alpha-emitting region, which does not necessarily correspond to the outer edge of the ejecta.

The H\alpha (6563 Å) line shows high-velocity outliers (both red- and blueshifted; see Table 5). These outliers do not appear to decelerate as long as they are present. In fact, the high-velocity outliers appear to accelerate throughout the first week of the nova’s evolution, although this could be the result of blending with lines from He I (6678 Å) and Fe II (6455.8 and 6456.4 Å) that are not detectable until later in the nova’s evolution. We show the evolution of the high-velocity outliers in Figures 5 (blueshifted) and 6 (redshifted). These outliers could be explained by a shell of high-velocity material. However, the narrowness of the outlier lines would require that the shell had a very small thickness, and such a fast-moving thin shell should become diffuse (and thus undetectable) much faster than we see here. Another explanation is a bipolar outflow, where the narrowness of these high-velocity outliers would point to a relatively well-collimated outflow. It would also likely have a fairly small inclination angle for us to detect such large velocities. Such well-collimated bipolar outflows have been seen in several other novae. Examples of embedded novae with bipolar outflows are U Sco (Lépine et al. 1999) and Oph (Rupen et al. 2008; Sokoloski et al. 2008). None-embedded novae are also known to have bipolar outflows, such as V1494 Aql (Iijima & Esenoglu 2003), V475 Sco (Kawabata et al. 2006), V445 Pup (Woudt et al. 2009), V5668 Sgr (Banerjee et al. 2016), and possibly T Pyx (Chesneau et al. 2011).

The high-velocity outliers in Figures 2, 5, and 6 are likely to be H\alpha. We see marginal evidence for similar outliers with identical velocities around the H\beta line. Were these the [N II] lines, the 6482 Å line would be blueshifted by approximately 1150 km s\textsuperscript{-1}, while the 6668 Å line would be redshifted by only about 300 km s\textsuperscript{-1}. Low-velocity Fe II and He I lines appear in these regions around day 5 and strengthen as the ejecta evolve. Lacking other plausible identifications, we identify the outliers as H\alpha ejected at high velocities.

Using the H\alpha line width as the approximate velocity evolution for the optically thick component of the ejecta, we can use \( r(t) = \int_0^t v(t) dt \) to determine the approximate radial size of the ejecta at any given time \( t \). We perform this integration numerically using the trapezoidal approximation. First, we interpolate our velocity measurements to give a smoother function to integrate over. We assume that the velocity is constant between day 0 and our first spectroscopic measurement. This is likely an oversimplification, although it may not be drastically far from the average velocity over this time, as the ejecta must first be accelerated to some (unknown) maximum velocity and then decelerate to the velocity we measured with our first spectroscopic observation. Our

\footnote{\url{http://www.astronomy.ohio-state.edu/ANDICAM/detectors.html}}

Figure 1. Top panel: total count rate from Swift XRT. Second panel: count rate in the 0.3–1.0 keV energy range. Third panel: count rate in the 1.0–10 keV energy range. Bottom panel: hardness ratio (1.0–10 keV/0.3–1.0 keV). The dotted line indicates a ratio of 1.0.

Figure 2. Example optical spectrum of V1535 Sco obtained with the SMARTS telescope. This spectrum was from day 1.565. Note the high-velocity outliers on H\alpha (6563 Å).
resulting radial size of the H$\alpha$-emitting region is shown in the bottom panel of Figure 4.

The radial size of the H$\alpha$-emitting region can serve as a minimum size of the ejecta. A more realistic approximation of the radial size of the ejecta is to assume that the ejecta expand at roughly the velocity from the first observation: $\sim 1659 \text{ km s}^{-1}$. However, neither of these simple models accounts for the high-velocity outliers seen in the early spectra.

### 3. The Distance to V1535 Sco

The distance to V1535 Sco is highly uncertain. Srivastava et al. (2015) apply the maximum magnitude rate of decline (MMRD) relations from della Valle & Livio (1995) and Downes & Duerbeck (2000) to get distance estimates of $13.7 \pm 0.4$ kpc and $14.7 \pm 3.8$ kpc, respectively. However, Munari et al. (2017) reported a distance to V1535 Sco of approximately 9.7 kpc, despite using the same MMRD method as Srivastava et al. (2015). This indicates that the MMRD distance may be highly dependent on the data used, as Munari et al. (2017) performed all their observations on a single telescope and Srivastava et al. (2015) obtained their data from multiple telescopes via the American Association of Variable Star Observers. Furthermore, substantial uncertainty has been shed on the MMRD method in general by the work of Kasliwal et al. (2011) and Cao et al. (2012). The Srivastava et al. MMRD distances seem unlikely as they place the nova on the opposite side of the Galactic bulge, which should make it extremely reddened and obscured owing to the intervening material.

We were able to constrain the distance to V1535 Sco by using pre-outburst photometry to determine a spectral type for the companion. The source 2MASSJ1703261-350417 is within $0.4^\circ$ of V1535 Sco and has $J = 13.423 \pm 0.037$, $H = 12.500 \pm 0.033$, and $K = 12.190 \pm 0.041$. Without correcting for reddening, we find near-IR colors of $J - K = 1.233 \pm 0.078$ and $H - K = 0.310 \pm 0.074$.

Using the derived reddening from Srivastava et al. (2015) of $E(B - V) = 0.72 \pm 0.05$, we can compute the necessary color corrections. The reddening conversion functions of Schlafly & Finkbeiner (2011) give $E(J - K) = 0.413 \times E(B - V)$, $E(H - K) = 0.15 \times E(B - V)$, and $A_V = 0.723 \times E(B - V)$. Using these, we find the dereddened

### Table 4

| Day* | FWHM (Å) | FWHM Velocity (km s$^{-1}$) | FW3σ (Å) | FW3σ Velocity (km s$^{-1}$) |
|------|----------|-----------------------------|----------|-----------------------------|
| 1.565 | 47.5 | 1302 | 60.5 | 1659 |
| 2.491 | 37.3 | 1023 | 47.5 | 1304 |
| 4.493 | 36.0 | 987 | 45.8 | 1257 |
| 5.495 | 36.7 | 1006 | 46.7 | 1282 |
| 6.495 | 34.1 | 936 | 43.5 | 1193 |
| 7.484 | 32.8 | 899 | 41.8 | 1145 |
| 10.478 | 26.0 | 713 | 33.1 | 908 |
| 11.505 | 20.9 | 574 | 26.7 | 731 |
| 13.528 | 14.5 | 397 | 18.4 | 505 |
| 14.505 | 13.1 | 359 | 16.7 | 458 |
| 15.483 | 11.3 | 311 | 14.4 | 397 |
| 16.548 | 10.5 | 288 | 13.4 | 366 |
| 17.482 | 9.2 | 252 | 11.7 | 322 |
| 18.456 | 8.6 | 237 | 11.0 | 302 |
| 19.525 | 8.2 | 225 | 10.5 | 287 |
| 20.53 | 7.7 | 212 | 9.9 | 271 |
| 21.498 | 7.3 | 200 | 9.3 | 255 |
| 22.472 | 6.8 | 186 | 8.6 | 237 |
| 23.451 | 6.2 | 170 | 7.9 | 217 |
| 25.477 | 5.6 | 154 | 7.2 | 196 |
| 26.445 | 5.2 | 141 | 6.6 | 180 |
| 27.507 | 4.7 | 129 | 6.0 | 164 |
| 28.462 | 4.4 | 121 | 5.6 | 154 |
| 29.435 | 4.1 | 112 | 5.2 | 143 |
| 31.469 | 3.7 | 101 | 4.7 | 129 |
| 32.432 | 3.5 | 96 | 4.5 | 122 |
| 33.416 | 3.3 | 91 | 4.2 | 116 |
| 34.432 | 3.1 | 85 | 3.9 | 108 |
| 35.44 | 3.1 | 81 | 4.0 | 110 |
| 36.42 | 3.1 | 84 | 3.9 | 107 |
| 37.432 | 3.0 | 83 | 3.9 | 106 |
| 38.413 | 3.0 | 82 | 3.8 | 105 |
| 39.398 | 2.9 | 79 | 3.7 | 101 |
| 50.435 | 2.7 | 75 | 3.5 | 96 |
| 51.468 | 2.7 | 74 | 3.5 | 95 |
| 52.412 | 2.7 | 74 | 3.5 | 95 |
| 53.364 | 2.7 | 74 | 3.4 | 94 |
| 54.463 | 2.7 | 73 | 3.4 | 93 |
| 55.405 | 2.6 | 72 | 3.4 | 92 |
| 55.389 | 2.6 | 72 | 3.4 | 92 |
| 56.447 | 2.7 | 73 | 3.4 | 93 |
| 57.438 | 2.7 | 73 | 3.4 | 93 |
| 58.371 | 2.7 | 74 | 3.4 | 94 |
| 59.398 | 2.6 | 72 | 3.3 | 91 |
| 60.343 | 2.5 | 69 | 3.2 | 88 |
| 61.382 | 2.5 | 69 | 3.2 | 88 |
| 62.381 | 2.5 | 69 | 3.2 | 88 |
| 64.495 | 2.5 | 69 | 3.2 | 88 |
| 65.371 | 2.5 | 69 | 3.2 | 87 |
| 66.37 | 2.5 | 67 | 3.1 | 86 |
| 67.413 | 2.4 | 67 | 3.1 | 85 |
| 68.407 | 2.4 | 66 | 3.1 | 84 |
| 69.473 | 2.4 | 64 | 3.0 | 82 |
| 70.434 | 2.3 | 64 | 3.0 | 82 |
| 71.4 | 2.3 | 64 | 3.0 | 81 |
| 72.422 | 2.3 | 64 | 3.0 | 81 |
| 73.414 | 2.3 | 63 | 2.9 | 80 |
| 76.393 | 2.3 | 63 | 2.9 | 80 |
| 78.453 | 2.4 | 66 | 3.0 | 84 |
| 80.477 | 2.2 | 61 | 2.8 | 78 |
| 82.36 | 2.3 | 62 | 2.9 | 79 |
| 86.377 | 2.3 | 63 | 2.9 | 80 |
| 88.287 | 2.3 | 64 | 3.0 | 81 |

Note.
- We take the time of initial detection 2015 February 11.837 UT (MJD 57,064.837) to be day 0.0.
colors to be \((J - K)' = 0.936 \pm 0.098\), \((H - K)' = 0.202 \pm 0.081\), and \(J' = 12.902 \pm 0.073\), where the prime signifies that it is dereddened. Using the spectral class system of Covey et al. \(2007\), the colors are consistent with spectral classes from K3 III to M0 III, which, in turn, give an absolute \(J\) magnitude between \(-3.92\) and \(-4.75\). This gives a distance modulus of \(m_M = 15.212 \pm 1.253\), or a distance between 6.2 and 19.6 kpc. If we instead use \(E(B - V) = 0.96\), as reported in Munari et al. \(2017\), our distance range is 5.8–14.0 kpc.

Note that although we cannot definitively rule out the companion being a main-sequence star using this method, if it were a main-sequence progenitor system, the distance modulus would be \(<8\) mag. Since the peak brightness of the nova was \(m_V \approx 9.5\), the absolute magnitude at peak would be \(M_V > 1.0\), which is far too dim for a nova. Therefore, we can reasonably rule out a main-sequence companion. We therefore find it more likely that the companion star is an evolved star in the range between subgiant and giant.

Because the progenitor distance is consistent with being located at the Galactic center, and that is also where we expect most novae to occur, we can assume a distance of \(\sim 8.5\) kpc for V1535 Sco. This distance agrees well with estimates in Munari et al. \(2017\) based on both MMRD and the Buscombe & de Vaucouleurs \(1955\) method of estimating the absolute magnitude 15 days after optical maximum.

4. Results

4.1. VLA Light Curve and Spectral Indices

The full VLA light curves for V1535 Sco are presented in Figure 7. The nova was initially detected at relatively high flux densities, faded substantially, and then rose again to secondary peak around day 25. This secondary peak is unusual for novae, but not unprecedented (e.g., Taylor et al. \(1987\); Eyres et al. \(2009\); Krauss et al. \(2011\); Weston et al. \(2016\); Finzell et al. \(2017\)). After day 27, the source faded again until about day 56, when there is a tertiary peak. This is highly unusual. After the tertiary peak, the nova fades until it is no longer detectable.

The radio light curve for V1535 Sco is significantly different from the radio light curve of a nonembedded nova. In a “typical”
nonembedded nova, the radio emission is delayed from the optical emission by up to ~2 weeks and then slowly rises to a maximum over several months. This is due to the fact that nonembedded novae are typically thermal sources at radio wavelengths. Therefore, their flux density is directly related to the size of the ejecta. As the ejecta expand, the size of the emitting surface area increases, and so does the flux density (e.g., Hjellming 1996; Seaquist & Bode 2008). In contrast, the radio light curves for embedded novae are dominated by synchrotron radiation in the first weeks and therefore have high flux densities early and fade as the ejecta cool (e.g., O’Brien et al. 2006).

We measured the spectral index $\alpha$ (using $S_{\nu} \propto \nu^{\alpha}$) for each of our VLA observations. We fit the flux densities to a power law using the nonlinear least-squares curve_fit function in the SciPy package of python, weighted by the $\sigma$ uncertainties. We ignored upper limit values for this fit, using only solid detections. If two observations were separated by less than 24 hr, they were combined to make a single spectral index measurement. Our calculated spectral indices are presented in Table 6, including the associated $\sigma$ uncertainties from the variance-covariance matrix.

The evolution of the spectral index is shown graphically in Figure 8. During the first week of its evolution, the nova’s radio spectral index rises toward lower frequencies, an indicator of optically thin synchrotron emission. The spectral index then switches to rising toward higher frequencies. This is typical of sources emitting via optically thick thermal bremsstrahlung. To our knowledge, such a dramatic switch between a synchrotron-like $\alpha$ and a thermal-like $\alpha$ has never been seen before. However, the spectral index of V1324 Sco showed evidence of being negative at early times followed by a positive slope later (Finzell et al. 2017), and Eyres et al. (2009) reported the presence of both positive and negative spectral indices present simultaneously for RS Oph. At the tertiary peak around day 56, the spectral index switches to rising toward higher frequencies. This apparent switch from a thermal-like to synchrotron-like spectral index is unprecedented. As the nova fades, its spectral index flattens as expected for an optically thin thermal bremsstrahlung source.

The evolution of V1535 Sco’s radio spectral index is very different from the majority of classical novae. Typically, the radio emission begins with a positive (rising toward higher frequencies) spectral index while the ejecta is optically thick. As the ejecta becomes optically thin, the radio spectral index flattens to around $-0.1$. This transition from strongly positive to flat begins with the highest frequencies first and progresses through the lower frequencies as the ejecta dims overall. Even in novae where shocks are detected such as V959 Mon, the spectral index at early times is still usually positive (Chomiuk et al. 2014). A negative spectral index, especially during the first few weeks of a nova’s evolution, usually occurs in systems with evolved companions producing a strong wind for the nova ejecta to shock against, as in RS Oph (e.g., Eyres et al. 2009).

### 4.2. VLBA Compact Emission

Our VLBA detection on 2015 February 19 (Figure 9) was simultaneous with VLA L-band and C-band observations.
Using Difmap, we modeled the VLBA detection as a circular Gaussian in the \( uv \)-plane. The resulting total flux density is 0.477 mJy, with an off-source image rms of 0.044 mJy beam\(^{-1}\) and a diameter of 6.52 mas. The resolving beam for this observation was 2.5 \( \times \) 12.4 mas, so this could indicate a resolved source.

The brightness temperature \( (T_B) \) in K is given by the Rayleigh–Jeans relation (e.g., Rohlfs & Wilson 2006)

\[
S_\nu = \frac{2 k_B T_B \Omega}{\lambda^2},
\]

where \( S_\nu \) is the flux density in erg s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\) at frequency \( \nu \), \( \lambda \) is the observing wavelength in cm, \( k_B \) is the Boltzmann constant in erg K\(^{-1}\), and \( \Omega \) is the solid angle of the source. For a resolved source with a circular Gaussian shape, \( \Omega = \pi \theta_D^2 (4 \ln 2)^{-1} \), where \( \theta_D \) is the angular diameter of the source in radians. Therefore, the brightness temperature is calculated using

\[
T_B = \frac{2 \ln 2 S_\nu \lambda^2}{\pi k_B \theta_D^2}
\]

for our source. This gives a brightness temperature of 5.8 \( \times \) 10\(^5\) K. This is significantly lower than the 10\(^7\) K \( T_B \) of the synchrotron components in RS Oph (Rupen et al. 2008). However, we emphasize that our observation was made with lower resolution owing to the dropout of the Maunakea antenna. It is possible that our single structure is actually composed of two or more components that are too compact to resolve with our configuration. Modeling the source as two point sources results in a similar total flux density (0.445 mJy) and image rms (0.04 mJy beam\(^{-1}\)) with the same reduced \( \chi^2 \) (1.09) as the circular Gaussian model. If we make the assumption that the angular size of the components is equal.

**Figure 8.** SED of VLA observations plotted for each epoch. Nondetections are indicated by red downward-pointing triangles. The fit to the same-day data is shown as a dashed cyan line, and the spectral index value is given in cyan.

**Figure 9.** 4.87 GHz VLBA image of V1535 Sco on 2015 February 19 (day 7.6). The gray ellipse in the lower left corner indicates the shape and size of the restoring beam. The apparent extension to the southeast is likely an imaging artifact resulting from imperfectly calibrated data. The image is 0\(^{\prime\prime}1\) on a side.
to the minor axis of the restoring beam (2.5 mas), the resulting $T_B$ estimates are $1.8 \times 10^8$ K and $1.9 \times 10^8$ K. These are still lower than the $T_B$ for RS Oph, but are consistent with the $T_B$ for the compact components in V959 Mon (Chomiuk et al. 2014).

The simultaneous VLA flux density at 4.55 GHz was 0.650 mJy. Because the VLBA is only sensitive to high brightness temperature (i.e., compact) emission and the spectral index from the VLA observations of the nova ejecta was negative (i.e., larger flux density at lower frequencies), we conclude that the VLBA emission is most likely from synchrotron radiation. The compact emission on this day dominated the total emission at the 73% level. The excess VLA radio flux on this day may be due to thermal bremsstrahlung emission from the shocked plasma or the preshocked, cooler outflow.

Using the VLBA flux density of the single circular Gaussian model component, we estimate the magnetic field strength using the revised equipartition formula from Beck & Krause (2005). This formula requires knowledge of the path length through which the radiation propagates $l$, the filling factor of the emitting material $f$, the inclination angle of the field $i$, and the proton-to-electron number density ratio $K_\alpha$:

$$B \propto \left( \frac{K_0}{l f \cos(i)(1-\alpha)} \right)^{1/(3-\alpha)},$$

where $\alpha$ is the radio spectral index ($S_\nu \propto \nu^\alpha$). To make our estimate, we will assume a filling factor of 1 and an inclination angle of 0 (i.e., the field is face-on). For $l$, we assume that the emitting region was relatively thin, $\sim 10%$ of the radius of the H$\alpha$-emitting region (see Figure 4) at the time of the observation, which gives us $l \sim 9 \times 10^{12}$ cm. We used the typical values for $K_0$ of 40 and 100. The resulting magnetic field strengths were 0.14 G for $K_0 = 40$ and 0.18 G for $K_0 = 100$. If we assume that the path length is $\sim 10%$ of the radius of an ejecta shell expanding at a constant velocity of 1659 km s$^{-1}$ (the maximum velocity measured from the H$\alpha$ line width), we get $l \sim 10^{13}$ cm and a magnetic field of 0.13 G for $K_0 = 40$ and 0.17 G for $K_0 = 100$. If we assume that the path length is $\sim 10%$ of the radius of an ejecta expanding at a constant velocity of 4782 km s$^{-1}$ (the median velocity from the high-velocity outliers in the H$\alpha$ spectra over the first 5.5 days), we get $l \sim 3 \times 10^{12}$ cm and a magnetic field of 0.10 G for $K_0 = 40$ and 0.13 G for $K_0 = 100$. These values are all larger than, but still comparable to, the magnetic field strengths estimated for RS Oph of $0.03(1 + K_0)^{3/2}$ (Rupen et al. 2008).

Assuming the same values of $K_0$ as we used, the RS Oph magnetic field strength was between 0.087 and 0.11 G. It should also be noted that Rupen et al. (2008) estimated the magnetic field for RS Oph over 20 days after the eruption, whereas we are estimating the field for V1535 Sco only 7.7 days after eruption. It is possible that the magnetic field declines over time as the ejecta expand and the shocks dissipate.

4.3. Optical and Near-infrared Photometry

The optical and near-infrared light curve for V1535 Sco is not consistent with light curves for other novae known to have red giant companions (see Figure 10). In particular, when one considers the difference between the peak magnitude and the current magnitude (right panels of Figure 10), V1535 Sco is clearly an outlier. In other novae with red giant companions, the companion star begins to dominate the difference light curve at longer wavelengths relatively early, while the shorter wavelengths are still dominated by the nova ejecta. V1535 Sco, on the other hand, does not follow this behavior. Instead, all wavelengths fade together for the duration of the light curve. This indicates that the companion star is unlikely to be a red giant. However, the presence of synchrotron emission in the radio (Sections 4.1 and 4.2), the hard X-ray emission, and the rapid fading of the optical light curve all indicate that the nova ejecta were shocking against an external medium.

One possible explanation is that the companion star is not an M giant, but a K giant. We tested this hypothesis by fitting our optical and near-infrared fluxes with a model that combined a hot accretion disk and a stellar spectral energy distribution (SED) for a K giant star.

The quiescent unreddened optical colors of V1535 Sco are close to 0. We modeled the optical–infrared (OIR) SED as the sum of a mid-K giant plus an active accretion disk. The accretion disk is constructed following the Bertout et al. (1988) formalism. The optically thick disk is constructed of a series of annuli, each of which emits as a blackbody at a temperature set by its distance from the star. We set the inner edge of the accretion disk to the radius of a white dwarf; exact details are not important since the boundary layer and the inner edge of the disk emit in the ultraviolet. On the red side of the peak, the accretion disk follows a power law $F_\nu \sim \nu^{-0.2}$. With seven OIR fluxes, the model is underconstrained. We fix the extinction $A_V$ to be 2.16 mag and set the distance to 8.5 kpc. We constrain the white dwarf to be hot. We constrain the donor star to be K5 III, with $VJK$ colors taken from Kormneef (1983). Free parameters in the fit are the magnitude of the donor star and the mass accretion rate. An example of a fit is shown in Figure 11.
Figure 11. Fit to the SED on 2017 April 2 with an active accretion disk and a K5 III star. Model details are described in the text. Filled circles are the observed data. The open white circles are the dereddened observations; open red circles are the data after subtracting the K5 III SED. The green and blue dashed curves are the fits to the accretion disk and the star, respectively. The red dashed curve is the dereddened fit to the accretion disk. The fit underpredicts the observed J and H fluxes.

We fit the 10 SEDs obtained between 2016 April 25 and 2017 April 02. Over that year the donor star K faded by 0.15 ± 0.07 mag. This fading could be a cooling after irradiation by the nova, or it could be part of a longer-term variation. The mean fit K of 12.14 is consistent with the 2MASS K magnitude. Meanwhile, the mass accretion rate has dropped linearly by a factor of 6, from 12 to 2 × 10⁻⁹ M⊙ yr⁻¹. Numbers should be taken with a grain of salt. The mass accretion rate and the assumed distance are strongly correlated where the inferred mass accretion rate scales as the cube of the inferred distance.

Using our fits and assuming a distance of 8.5 kpc, we find that the absolute J magnitude for V1535 Sco in quiescence should be −1.2. Covey et al. (2007) give the absolute J magnitude for a K3 III star as −1.13, which is remarkably close for such a simple model. Munari et al. (2017) also conclude that the companion in V1535 Sco is consistent with a K3−4 III giant.

4.4. Optical and Near-infrared Spectroscopy

Srivastava et al. (2015) presented measurements of the velocity for V1535 Sco based on the Paβ emission line at 1.2818 μm starting 7 days after the detection and ending 40 days after the detection. Their velocities are given as FWHM of the line. As with our Hα measurements, we approximate the FW3σ velocities by applying the same calculation as described in Section 2.4. We then fit the line width versus time data with a power law using the nonlinear least-squares curve_fit technique in the SciPy package of python. Our resulting fit is somewhat different from that given in Srivastava et al. (2015). They report a power law of \( t^{-0.89±0.14} \), whereas our fit gives \( t^{-1.13±0.17} \). However, we should note that we are uncertain as to the methods used by Srivastava et al. (2015) because they do not describe their fitting procedure in detail. To compare the Paβ results with our more densely sampled Hα data, we fit our Hα FW3σ measurements from day 7.48 to day 39.4 using the same SciPy method and find a power law of \( t^{-1.49±0.05} \), which nearly agrees within uncertainties with the Srivastava et al. (2015) value. Of course, this simple power-law fit completely ignores the complicated behavior observed during the first week following the explosion (see Figure 4).

The SMARTS optical spectroscopic monitoring of V1535 Sco also revealed blueshifted Hα absorption features. These features become noticeable around day 15, after the Hα line has narrowed significantly (see Figure 12). The blueshifted features have an initial velocity of \( ~500 \text{ km s}^{-1} \), but slow to \( ~50 \text{ km s}^{-1} \) by day 247. These absorption features indicate the presence of a large amount of cool, neutral material ahead of the Hα-emitting region. It is possible that this neutral material was preshocked wind material being swept up by the nova ejecta in a “snowplow” fashion.

4.5. X-Rays

We fit the Swift data using the XSpec version 12.8.2 package. The spectra were best fit using a combination of a blackbody (BB) and a thermal plasma (apec). The apec model includes contributions from free−free continuum and lines (Smith et al. 2001). Only the first five detections had high enough signal-to-noise ratios to successfully model the emission. The results are given in Table 7. The hydrogen column density \( (N_H) \) appears to be fairly constant throughout the first 18 days, with a deviation on day 11, which is most likely the fitting software getting stuck in a local minimum. This constant \( N_H \) is quite different from the sharply decreasing \( N_H \) observed in the embedded novae RS Oph (Bode et al. 2006) and V745 Sco (Page et al. 2015). The blackbody temperature appears to decrease by only a factor of 2 over the first 25 days, with a minor fluctuation around day 17.9. The hot plasma temperature, on the other hand, dramatically cools by at least 2 orders of magnitude during the same time period. This is likely due to the shocks expanding and becoming radiatively efficient.

The \( E(B−V) \) of 0.96 reported by Munari et al. (2017) implies \( N_H \approx 5 \times 10^{21} \text{ cm}^{-2} \) (Predehl & Schmitt 1995). Our values of \( N_H \) are nearly twice this, indicating a local enhancement from a possible stellar wind. Interestingly, our
Notes.

a All observation IDs are 0003363400X.

b We take the time of initial detection 2015 February 11.837 UT (MJD 57,064.837) to be day 0.0.
5.1. Expected Brightness Temperature for VLBA Source

Using the radial size, we can estimate what we expect the brightness temperature of the ejecta to be at the time of the VLBA observation using

$$T_B \approx \frac{S_v c^2 D^2}{2 \pi k_B v^2 R^2},$$  \hspace{1cm} (4)$$

where $R$ is the radius of the spherically expanding ejecta and $D$ is the distance to the source (e.g., Seaquist & Bode 2008). We will start by assuming that the size of the radio-emitting region is the same as that of the H$\alpha$-emitting region. From our fit to the H$\alpha$ line widths presented in Section 2.4, we derive a radius for the H$\alpha$-emitting region of $8.98 \times 10^{13}$ cm on day 7.663. Using only the VLBA flux of 0.477 mJy and assuming a distance of 8.5 kpc, this gives $T_B \approx 1.8 \times 10^7$ K. Alternatively,
the radius could be the distance traveled by ejecta moving with a velocity of 1659 km s\(^{-1}\), which gives us 1.10 \(\times\) 10\(^{14}\) cm. Using the VLBA flux and a distance of 8.5 kpc, this material would have a \(T_B\) \(\approx\) 1.2 \(\times\) 10\(^7\) K. Both of these are significantly higher than the estimate of 5.8 \(\times\) 10\(^5\) K using the distance-free formula for \(T_B\) in Section 4.2. To get the largest possible radius, we could assume that the ejecta were traveling at 4782 km s\(^{-1}\) for 7.663 days, giving a radius of 3.17 \(\times\) 10\(^{14}\) cm and \(T_B\) \(\approx\) 1.4 \(\times\) 10\(^6\) K. The discrepancy between the observational and expected \(T_B\) can indicate several possibilities: first, the ejecta were unresolved by the VLBA; second, the nova is much closer than 8.5 kpc; third, the ejecta shape is highly nonspherical; or some combination of these reasons. We should note that the expected \(T_B\) using the largest possible radius agrees well with the observational \(T_B\) assuming two point sources. However, using the largest possible radius would only give us a single sphere with an angular size of 2.5 mas at 8.5 kpc (which just happens to be the minor axis of the VLBA restoring beam for our observation), not the two point sources modeled in Section 4.2, so we cannot reconcile the measurement with the observation quite so easily.

From Section 3, recall that the closest the nova can be is 5.8 kpc. At this distance, the brightness temperature would be 8.3 \(\times\) 10\(^6\) K for a radius of 8.98 \(\times\) 10\(^{13}\) cm, 5.5 \(\times\) 10\(^6\) K for a radius of 1.10 \(\times\) 10\(^{14}\) cm, or 6.7 \(\times\) 10\(^5\) K for a radius of 3.17 \(\times\) 10\(^{14}\) cm. The first two are still larger than the value of 5.8 \(\times\) 10\(^5\) K we calculated for the single-component model in Section 4.2, although they are comparable to the two-component model. The final one, using our maximum possible radius, agrees well with the single-component model \(T_B\) in Section 4.2. However, recall that we find it more likely that the high-velocity outliers in the H\(_\alpha\) spectra represent a bipolar outflow, not an expanding spherical shell.

Note that this approach to estimating what the brightness temperature should be at the time of the VLBA detection assumes that the entire surface of the ejecta shell is emitting. If the emission is coming from compact, jet-like structures as in RS Oph (Rupen et al. 2008; Sokoloski et al. 2008), the value for \(R\) would be smaller and the estimate for \(T_B\) would be even larger. Placing the nova at further distances also increases the estimate for \(T_B\).

Because placing the nova closer does not make the values of \(T_B\) match, it is more likely that the VLBA did not fully resolve the compact emitting region on day 7.663. Because of the highly elliptical shape of the restoring beam, it is especially likely that there is unresolved structure in the north–south direction. However, the image does look like there is some resolved structure in the east–west direction. We find it likely that the compact component is nonspherical, possibly bi-lobed, and with more extension in the east–west direction.

### 5.2. X-ray and Radio Emission Measures near Day 25

We used the emission measures for both radio and X-ray to investigate whether the secondary maximum in the radio light curve that occurs between days 23.663 and 26.563 can be explained by thermal radio emission from the X-ray-emitting plasma. For the X-rays, the emission measure depends on the volume of the emitting region:

\[
EM_x = \int n_i n_e dV,
\]

where \(n_i\) and \(n_e\) are the number densities of ions and electrons, respectively, and \(V\) is the volume of emitting material. Generally it is assumed that \(n_i \approx n_e = \text{constant}\), so that it simplifies to \(EM_x \approx n_i^2 V\). To make a further simplification, the emitting volume is assumed to be thin compared to the total extent of the ejecta, so that it can be approximated as a uniform slab: \(V \approx \pi r^2 dl\), where \(r\) is the radius of the ejecta (we are assuming that the emitting region can be approximated as a cylinder) and \(dl\) is the thickness of the emitting region. The X-ray emission measure can be determined from the hot plasma parameters in the fits to the \textit{Swift}\ data:

\[
EM_x = (4 \times 10^{14}) \pi D^2 \text{norm}_{\text{apec}},
\]

where \(D\) is the distance to the nova. Assuming a distance of 8.5 kpc (placing the nova approximately at the Galactic center) and using \text{norm}_{\text{apec}} from day 24.75 (see Table 7) gives \(EM_x \approx 2.25 \times 10^{58} \text{ cm}^{-3}\). Assuming that the ejecta travel with a constant velocity of 1659 km s\(^{-1}\), we can determine that the approximate radius for the shell on day 24.75 was 3.5 \(\times\) 10\(^{14}\) cm. If we assume that the thickness of the emitting shell is \(\sim 10\%\) of its radius, we can solve for the number density of the emitting electrons: \(n_e \approx 4.0 \times 10^7 \text{ cm}^{-3}\) emitting at a temperature of approximately 10\(^6\) K (from \(kT_{\text{apec}}\) in Table 7). Note that if we assume a larger distance to the nova, both \(EM_x\) and \(n_e\) increase.

The radio (path length) emission measure is given by

\[
EM_r = n_i^2 \, dl;
\]

plugging in the same \(dl\) (but this time in pc) used for \(EM_x\), and using \(n_i\) derived from the X-ray data gives \(EM_r = 1.8 \times 10^{19} \text{ cm}^{-6}\) pc. The radio emission measure is also part of the equation for optical depth, \(\tau_v\) (Rohlfs & Wilson 2006):

\[
\tau_v = 8.235 \times 10^{-2} T_e^{1.35} \nu^{-2.1} EM_r a(\nu, T).
\]

Therefore, another way to calculate the radio emission measure is given by

\[
EM_r = 12.143 T_e^{1.35} \nu^{-2.1} a(\nu, T)^{-1},
\]

where \(T_e\) is the electron temperature in K, \(\nu\) is the observing frequency in GHz, \(\tau_v\) is the optical depth at the observing frequency, and \(a(\nu, T)\) is a correction term usually assumed to be 1. In order for the emission to be optically thick at the observed frequency, \(\tau_v \geq 1\). Because we are trying to determine whether the radio flux can be explained by the X-ray plasma, we set \(T_e \approx 10^6\) K from the \(kT_{\text{apec}}\) value from the fits to the \textit{Swift}\ data on day 24.75 (see Table 7). We use our highest observing frequency of 36.5 GHz because it provides the tightest constraint. This gives us \(EM \approx 2.92 \times 10^{12} \text{ cm}^{-6}\) pc, which is more than two orders of magnitude larger than expected from the X-ray electron number density used above. Therefore, under the reasonable assumptions we have made, the X-ray-emitting plasma cannot account for the thermal radio emission detected around day 24. It is more likely that there is
also a warm (~10^4 K) ionized ejecta that begins to dominate the radio emission at this time.

Unfortunately, the uncertainty on $n_{\text{spec}}$ from day 24.75 is very high. If we use the $n_{\text{spec}}$ value from day 17.93 with its much lower uncertainty and assume that the number density remains mostly constant until day 24, we get $n_r = 1.7 \times 10^7 \text{ cm}^{-3}$, which would imply $E_M = 2.4 \times 10^{48} \text{ cm}^{-6} \text{ pc}$. This makes the discrepancy between the two methods for determining the radio emission measure even greater, further strengthening our argument that the X-ray-emitting plasma cannot account for the radio flux density observed during the second radio maximum.

6. Conclusions

V1535 Sco showed peculiar behavior at nearly every wavelength we observed. The radio emission started bright, faded quickly, and then had two rebrightening events. The spectral index for early radio emission and the second radio rebrightening event were consistent with optically thin synchrotron emission. The X-ray emission began promptly with a hard spectrum. There was a rebrightening in the X-rays that appeared to correspond to the second rebrightening event in the radio. The lack of connection between the first radio rebrightening event and the X-ray emission implies that there are at least two emitting components in the ejecta: one shock-heated plasma and one thermal bremsstrahlung. The optical observations indicate that the nova was discovered post-peak and faded very fast. Optical spectroscopy also indicated the presence of two outflows: (1) a relatively slow (~1659 km s$^{-1}$) outflow, and (2) a fast (~4782 km s$^{-1}$), possibly bipolar outflow. Spectral monitoring of the H$\alpha$ line at late times also indicated the presence of a neutral, dense surrounding cloud of emitting material.

The early hard X-rays combined with the radio synchrotron emission and the detection with the VLBA strongly support the existence of strong shocks very early in the evolution of the nova. Such early strong shocks are most easily explained by the presence of a dense wind from the companion star. The estimated magnetic field from the VLBA detection was between 0.10 and 0.18 G, which is larger than but comparable to the magnetic field strength found by Rupen et al. (2008) for RS Oph, a system known to have a red giant companion.

There was evidence for a second shock around day 50. The radio spectral index at this time changed from being consistent with optically thick thermal bremsstrahlung to being synchrotron-like. The X-ray emission also showed an increase at this time. We posit that this second shock was the result of collisions between multiple outflows within the ejecta, but the presence of a shell of dense material (possibly from a previous eruption) has not been completely ruled out.

The nova had strong hard X-ray emission early in its evolution, but no detectable $\gamma$-rays. However, it should be noted that V1324 Sco is the only nova Fermi has detected that has distance comparable to V1535 Sco (Finzell et al. 2015). We also note that V745 Sco, with its red giant companion and presumably denser wind, was only marginally detected by Fermi (Cheung et al. 2014). It is very likely that V1535 Sco produced at least some $\gamma$-ray emission but it was simply too far away for Fermi to detect.

To date, only a handful of Galactic novae with red giant companions are known, including the recurving nova RS Oph and V745 Sco. However, recent studies on the nova population in M31 indicate that there may be many novae with red giants that are not detected, and they may constitute ~30% of the nova eruptions in the Milky Way (Williams et al. 2016). There is particular interest in discovering more of these novae because they are possible progenitors to Type Ia supernovae (e.g., Starrfield et al. 2012). In fact, Dilday et al. (2012) claim that the supernova PTF 11kx originated from such a system.

Novae that occur in a system with a red giant companion are often referred to as “symbiotic novae.” However, the term “symbiotic novae” is also used to describe a particularly slow and long-lasting class of novae where nuclear burning on the surface of the white dwarf is sustained for several years, and sometimes decades, such as PU Vul, HM Sge, and AG Peg (e.g., Iben & Fujimoto 2008). In order to avoid confusion and better describe the general class of thermonuclear novae with evolved companions, our collaboration has adopted the term “embedded nova” to refer to any nova that is embedded in the dense wind of its post-main-sequence companion star, regardless of the duration of its optical maximum (e.g., Chomiuk et al. 2012; Mukai et al. 2014).

We find some evidence that V1535 Sco is an embedded nova. The early strong, hard X-rays and nonthermal radio emission argue for the presence of a preexisting dense material to shock against. Also, the X-ray emission showed signs of absorption beyond what is expected for the measured $E(B-V)$, which also points to the nova being embedded in some preexisting cloud. The fast optical decline is also consistent with an embedded nova. However, the long-term behavior of the optical and near-infrared light curves was unlike that of other novae known to have red giant companions. We also did not observe the rapid decrease in $N_\lambda$ that previous X-ray observations of novae with known red giant companions have reported. We produced a model of the quiescent system as a K giant with an accretion disk that is in good agreement with the observed optical and infrared magnitudes. We therefore find that the companion star in this system is producing a significant stellar wind and is most likely a K giant, specifically a K3–5 III, which is in agreement with Munari et al. (2017). Several symbiotic binary systems with K giant stars are known, and they are often referred to as “yellow symbiotics” (e.g., Baella et al. 2016).

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Facilities: Karl G. Jansky VLA, VLBA, Swift, SMARTS.

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