



# Ancient Nova Shells of RX Pup Indicate Evolution of Mass Transfer Rate

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## Abstract

RX Pup is a symbiotic binary that experienced a nova outburst in the 1970s. Here we report a discovery of a  $\sim 1300$  yr old nova shell around the system and a possible detection of a  $\sim 7000$  yr old nova shell. Together with the nova shell ejected in the 1970s, this makes RX Pup the first system with three nova shells observed. This triad of eruptions suggests a change in the nova recurrence time. The most likely explanation is an alteration in the mass transfer rate attributed to evolutionary changes of the mass donor in the system. Notably, comparative analyses with theoretical models indicate an increase in the average mass transfer rate by a factor of 3 over the past 10,000 yr. This makes RX Pup a unique system, which allows us to probe millennium-scale evolution of mass transfer rates in binary systems.

*Unified Astronomy Thesaurus concepts:* Symbiotic binary stars (1674); Classical novae (251); Symbiotic novae (1675); Recurrent novae (1366)

## 1. Introduction

Symbiotic stars (SySts) are an interacting binary system in which a white dwarf (WD) or a neutron star is accreting matter from a red giant companion. They can experience classical nova (CN) eruptions, which occur on the surface of the WD when enough material is accumulated and a thermonuclear runaway is triggered (Starrfield et al. 1974; Prialnik et al. 1978). The material ejected during the eruption forms a nova shell that can be observed for millennia after the outburst (Shara et al. 2017; Tappert et al. 2020; Shara et al. 2024).

CNe in SySts are either extremely slow novae (usually called symbiotic novae (SyNe)), with outbursts going on for decades, or very fast recurrent novae (SyRNe), with very short,  $\sim$ several days, timescales and a recurrence time of  $\sim$ several years or decades. The differences in outburst behavior seem to reflect different WD masses: very high in SyRNe, close to the Chandrasekhar limit, and much lower in SyNe (Mikołajewska 2010).

RX Pup is an SySt with an orbital period of at least 200 yr and a extreme Mira donor pulsating with a period of  $\sim 578$  days (Mikołajewska et al. 1999). RX Pup experienced a CN outburst that started in the 1970s. The outburst evolution in the HR diagram was consistent with a slow SyN on a  $\sim 0.8 M_{\odot}$  WD (Mikołajewska et al. 1999). RX Pup produced a nova shell that was visible even during outburst (Hollis et al. 1989; Paresce 1990; Mikołajewska et al. 1999; Corradi & Schwarz 2000; Mikołajewska et al. 2002).

Mikołajewska et al. (1999) suggested that another nova outburst occurred in the 1890s; however, it could also have been a high state due to the enhanced accretion rate, similar to that observed in the late 1990s (Mikołajewska et al. 2002). We also note that recurrent CN outbursts have been recently reported for two other SySts, LMC S154 (Iłkiewicz et al. 2019b) and

V618 Sgr (Merc et al. 2023), both showing relatively slow outbursts more similar to SyNe than to SyRNe, suggesting less massive WDs. A possible solution to this conundrum may be their much higher mass accretion rates than those of CNe with unevolved donors, which would significantly shorten the CN recurrence time. In addition, evolved donors are bright in the optical red and near-infrared range, which makes it relatively easy to measure radial velocities from absorption lines and to derive reliable masses of the binary components. For this reason SyNe and SyRNe are a valuable tool for testing theoretical models of CN outbursts.

In this study, we report the discovery of an additional nova shell associated with RX Pup originating from a prior outburst, as well as a possible, even older nova shell.

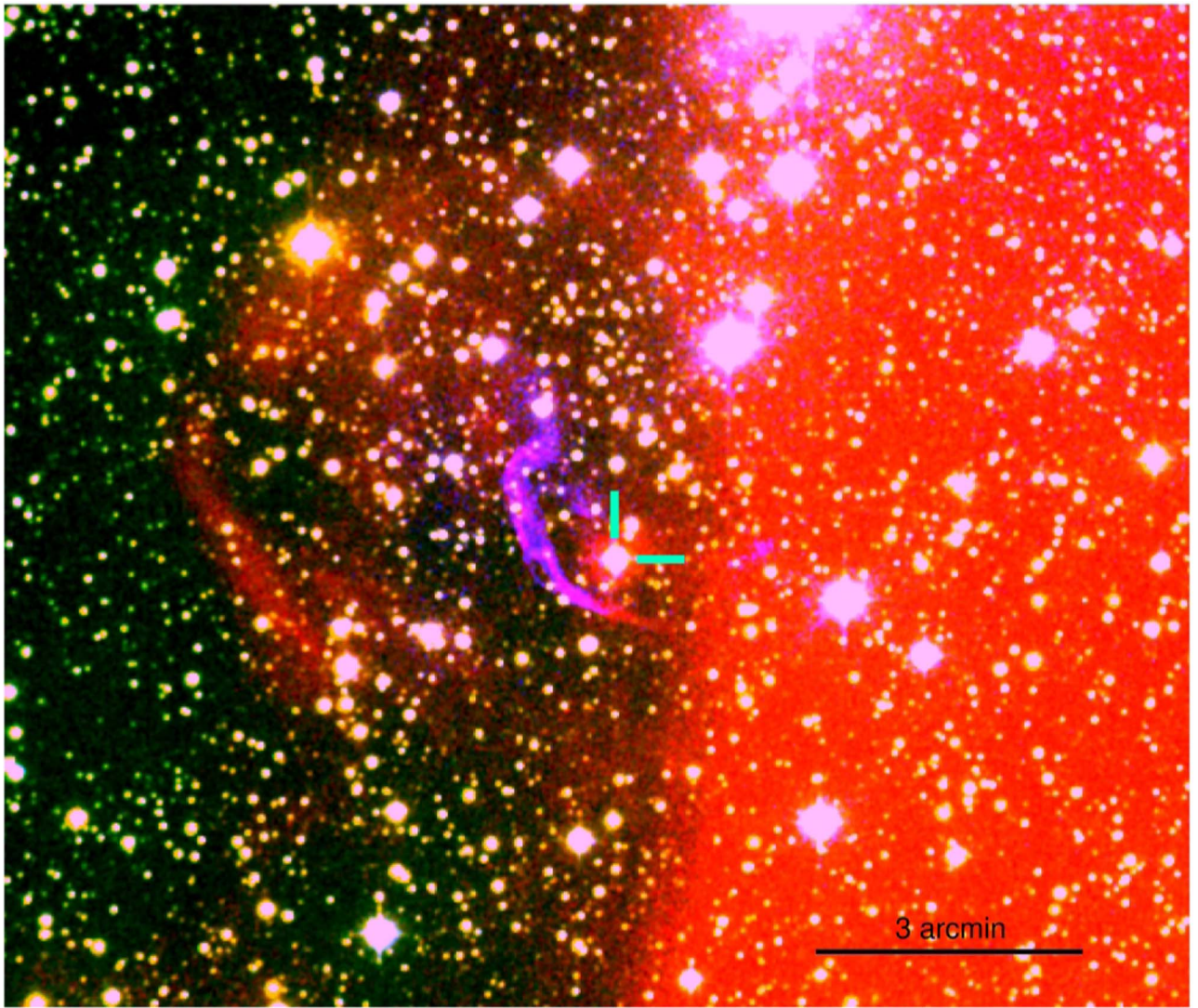
## 2. Observations

### 2.1. Narrow-band Imaging

We observed RX Pup with the 1 m Swope telescope at Las Campanas, Chile, on 2016 December 6–7. The telescope was equipped with a  $4K \times 4K$  E2V CCD231-84 camera, resulting in a  $30' \times 30'$  field of view. The observations were carried out in [O III],  $H\alpha$ , and  $R$  filters. This included  $2 \times 1200$  s and  $2 \times 2400$  s frames in  $H\alpha$ ,  $1 \times 1200$  s and  $3 \times 2400$  s in the [O III] filter, and  $2 \times 45$  s and  $3 \times 60$  s in the  $R$  filter. Each exposure was randomly offset to average out differences between the four independent detector amplifiers. The observations were reduced using standard IRAF procedures. The astrometry was applied using *Astrometry.net* (Lang et al. 2010). The observations were combined using the *SWarp* code (Bertin et al. 2002). A false-color image of RX Pup is presented in Figure 1.

### 2.2. Spectroscopy

Spectroscopy was carried out with the Southern African Large Telescope (SALT; Buckley et al. 2006; O'Donoghue et al. 2006) equipped with the Robert Stobie Spectrograph (Burgh et al. 2003;



**Figure 1.** False-color image of RX Pup with [O III] represented in blue,  $R$  in green, and  $H\alpha$  in red color. North is up, east is left. RX Pup is in the center of the image, indicated with turquoise ticks. The entirety of the image west of RX Pup is dominated by  $H\alpha$  emission of an unrelated nearby H II region. The  $\sim 1300$  yr old nova shell is seen as a bright [O III] and  $H\alpha$  emission  $43''$  east of RX Pup. A possible  $\sim 7000$  yr old shell is seen as a  $H\alpha$  shell centered on RX Pup and with a radius of  $240''$ .

Kobulnicky et al. 2003) and a PG0900 grating yielding a resolution of  $6.1 \text{ \AA}$ . The background subtraction was performed by fitting a low-order polynomial to the sky at each individual wavelength. This subtracted both the telluric emission as well as emission from the nearby H II region, leaving only the star spectra and more localized extended emission. Moreover, a low-order polynomial was fitted to spectra at each position on the slit in order to minimize noise from the background stars and scattered light from RX Pup itself. The observations were carried out at four positional angles and were centered at RX Pup (Figure 2). Each positional angle was chosen so that an additional star was on the slit. The distance on the sky between the additional star and RX Pup was used to calibrate the distance of features observed along the slit. Spectrophotometric calibration was performed using a standard star. However, absolute calibration was impossible due to the variable aperture of SALT. The list of spectroscopic observations is presented in the Appendix.

In order to identify features of the extended nebula around RX Pup, we extracted fluxes at  $H\alpha$  and [O III] 5007

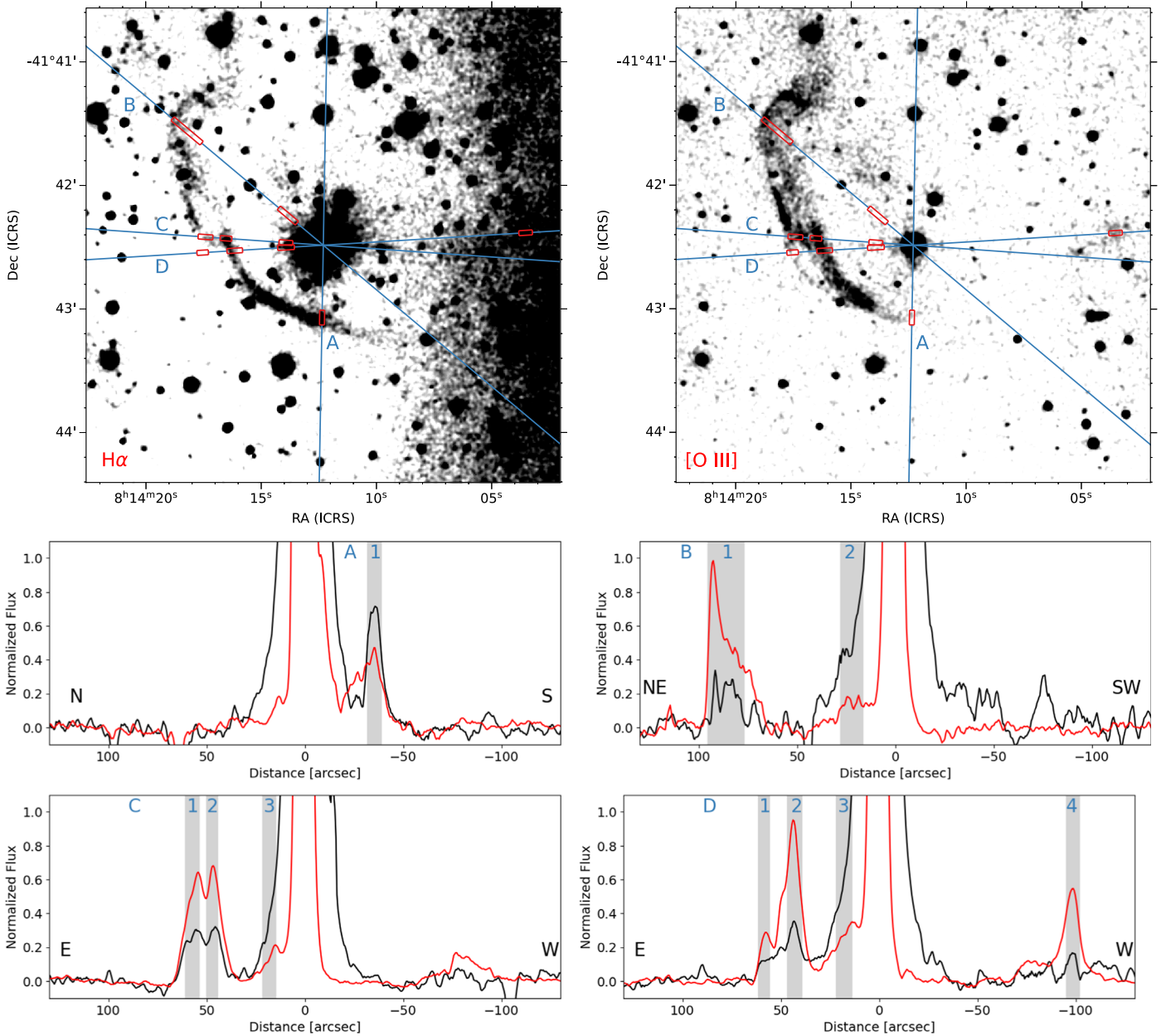
wavelengths along the slit. For each slit position we identified extended emission regions using the fluxes along the slit and compared them to imaging. The emission regions are marked with red rectangles in the top two panels of Figure 2 and were named and numbered as shown in the bottom four panels. For each of these regions a median spectrum was extracted. The spectra are presented in the Appendix.

The measured emission line fluxes for each region are presented in Table 1. The presented emission line fluxes are relative to the  $H\alpha$  line flux. The error of measured flux was of the order of  $\sim 10\%$  for the strongest lines and  $\sim 30\%$  for the weakest lines.

### 3. Results

We observed an extended emission that was bright in [O III] and  $H\alpha$  east of RX Pup. The emission forms an irregular arc extending from  $\sim 30''$  south to  $\sim 90''$  northeast of RX Pup (Figure 1). This arc clearly shows clumps of brighter emission in the [O III] band, while the emission in  $H\alpha$  is more continuous (Figure 2). Moreover, a faint [O III] emission



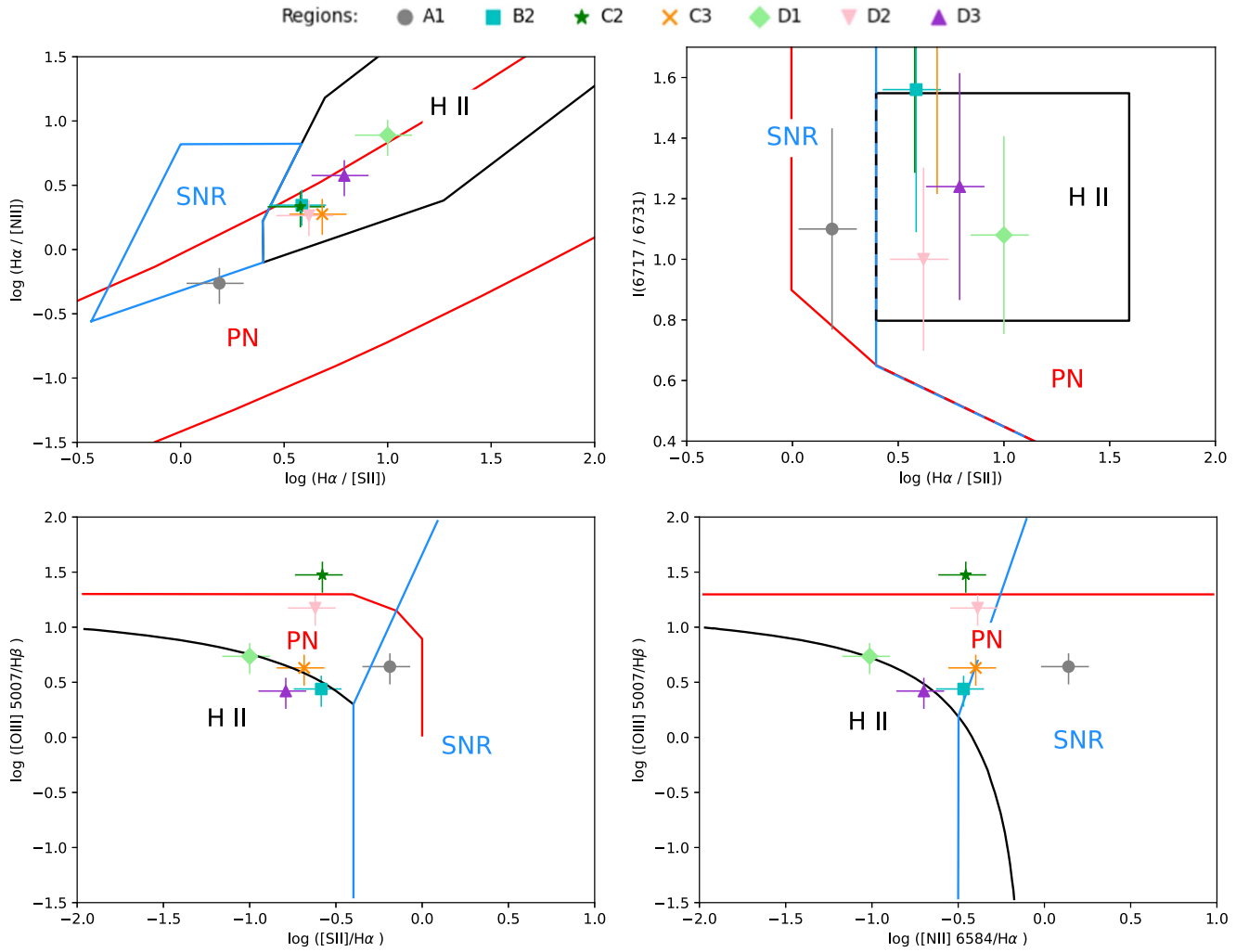


**Figure 2.** Top two panels:  $H\alpha$  and  $[O\ III]$  images of extended emission regions around RX Pup. Slit trails are marked with blue lines and named A–D with positional angles of  $179^\circ$ ,  $50^\circ$ ,  $86^\circ$ , and  $93.5^\circ$ . All slits were centered at the position of RX Pup. The identified extended emission regions along slit positions are marked with red rectangles. Bottom four panels: observed fluxes along slit positions (A–D) as a function of distance from RX Pup that were smoothed with a five-pixel-wide tophat filter. The direction on the sky from RX Pup is marked with black letters. The observed fluxes were at  $H\alpha$  (black line) and  $[O\ III]$  5007 (red line) wavelengths. For each slit position the identified extended emission regions are marked with a gray area. The extended emission regions are then numbered. The final assigned slit position name and the extended region number are marked with blue symbols.

region  $\sim 10''$  in diameter is present  $\sim 100''$  directly west of RX Pup. This clump of emission seems to not be visible in our  $H\alpha$  imaging. A more distant extended emission region bright in  $H\alpha$  is also present around RX Pup. While this emission is visible only east of RX Pup, it seems to form a half-ring with a  $\sim 4'$  radius centered at RX Pup. The entirety of the image  $\sim 1'$  west of RX Pup is dominated by an extended  $H\alpha$  emission from a nearby H II region that is not related to RX Pup.

The extended emission around RX Pup is reminiscent of a nova remnant (Figure 1). However, the presence of a H II region nearby RX Pup puts the immediate identification as a nova remnant in doubt. Diagnostic diagrams based on emission line ratios can identify different physical conditions in the

emission region, which can separate out different astrophysical objects (e.g., Sabin et al. 2013). Hence, to distinguish whether the extended emission is a nova remnant or if it is associated with the H II regions, we used such diagnostic diagrams. For this we calculated the  $H\beta$  intensity assuming Case B and RX Pup reddening  $E(B - V) \simeq 0.8$  mag (Mikołajewska et al. 1999). Moreover, we calculated  $[N\ II]$  6548 intensity assuming a 6583/6548 line ratio of three. While nova shells are not included in the diagnostic diagrams, a region directly south of RX Pup (region A1) falls within the supernova remnant (SNR) classification region (Figure 3). The supernova classification on these diagrams is based on line ratios observed in shocks, which could not be produced by a H II region. On the other



**Figure 3.** Diagnostic diagrams based on emission line ratios designed to distinguish between H II regions, PNe, and SNRs (Sabin et al. 2013). The measured line ratios for the nova shell around RX Pup are marked with colored markers. Region A1 has emission line ratios consistent with a SNR, suggesting a shock between the nova ejecta and the interstellar medium. The other regions' emission line ratios are consistent with low-density PNe, as expected for an old nova remnant.

**Table 1**  
Measurements of Emission Lines from Different Emission Regions around RX Pup (see Figure 2)

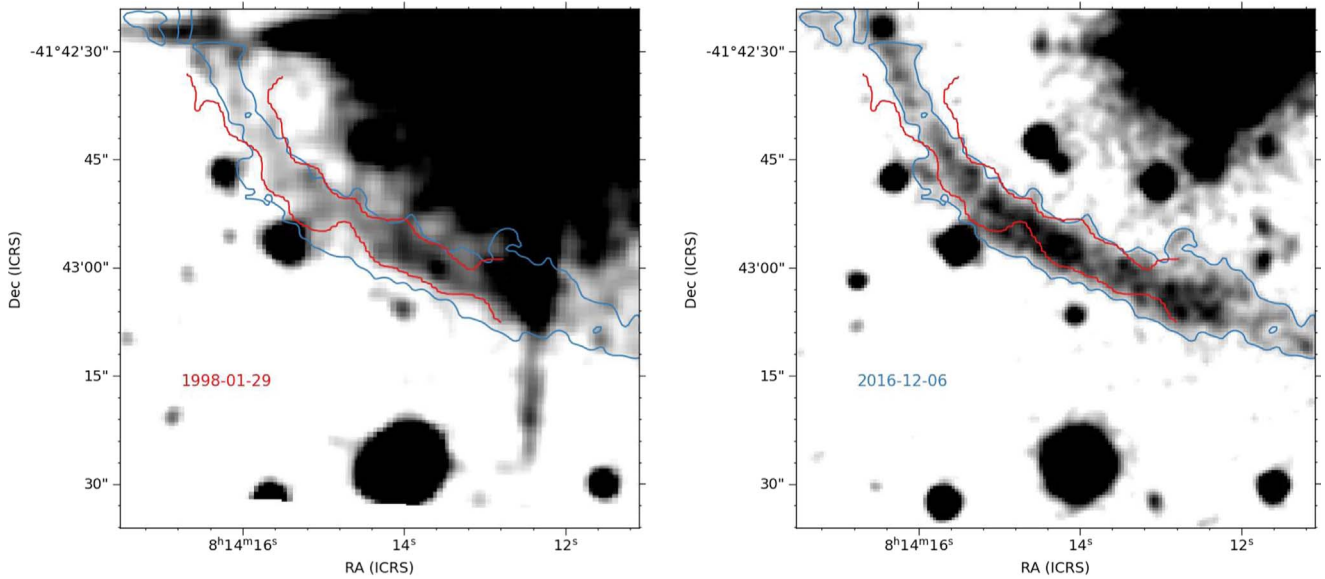
Region	[O III] 4959		[O III] 5007		[N II] 6548		H $\alpha$		[N II] 6583		[S II] 6716		[S II] 6731		[S II] 6716/6731	<RV>
	Flx	RV	Flx	RV	Flx	RV	Flx	RV	Flx	RV	Flx	RV	Flx	RV		
A1	23	85	84	65	53	48	100	50	145	51	40	59	34	50	1.18	$52 \pm 2$
B1	99	37	330	31	...	...	100	0	24	24	...	...	...	...	...	...
B2	...	...	47	-5	14	2	100	-1	34	-15	16	-3	10	-8	1.56	$-5 \pm 3$
C1	129	41	357	33	...	...	100	34	...	...	...	...	...	...	...	...
C2	159	35	510	24	...	...	100	25	35	16	17	32	9.4	20	1.84	$23 \pm 3$
C3	20	4	73	19	17:	-50:	100	-3	40	-21	13	-1	7.7	-16	1.74	$-10 \pm 5$
C4	239	37	822	25	...	...	100	60	78	-22	...	...	...	...	...	...
D1	33	43	93	25	...	...	100	23	9.7:	-42:	5.2:	-44:	4.8:	-34:	1.08:	...
D2	83	15	255	20	15	18	100	17	41	14	12	-8	12	-4	1	...
D3	18	44	45	45	9.6	-15	100	-17	20	-34	9	-14	7.2	-6	1.24	$-17 \pm 5$
D4	150	12	477	18	...	...	100	11	...	...	...	...	...	...	...	...

**Notes.** The fluxes are relative to the flux of the H $\alpha$  emission line. The radial velocities are in km s $^{-1}$ .

Flx — relative emission line fluxes; RV — the radial velocities in kilometres per second; [S II] 6716/6731 — ratio of [S II] 6716 to [S II] 6731 line fluxes; <RV> — mean radial velocities of all emission lines not including the the [O III] lines.

hand, it is consistent with interaction between the nova ejecta and interstellar medium, producing a shock similar to the one observed in the case of SNRs. Hence, we conclude that the

nova remnant classification is correct. Since similar shocks produce X-ray emission we searched for X-ray emission associated with the nova ejecta of RX Pup. In fact an X-ray



**Figure 4.** SuperCOSMOS (left) and Swope (right) images of the irregular arc east of RX Pup revealing expansion of the nova shell. The red contour shows position of the nova shell in the SuperCOSMOS image (1998), and the blue contour shows its position on the Swope image (2016). The SuperCOSMOS image has been smoothed with a four-pixel-wide Gaussian filter.

source 4XMM J081413.4-414256 is present nearby the location of the emission arc [O III] maximum flux at a positional angle of  $155^\circ$  relative to RX Pup (Webb et al. 2020). While we did not identify any optical counterparts of this X-ray source other than the irregular emission arc, a more detailed study is needed to confirm an association between 4XMM J081413.4-414256 and the nova shell. The other emission regions do not show evidence of shocks. However, they overlap the region occupied by low-density planetary nebulae (PNe), as expected for an old nova remnant. We suppose that the D4 emission clump west of RX Pup is part of the nova remnant since it is the only [O III] emitting region within the nearby H II region.

As for the  $\sim 4'$  half-ring its possible identification as a nova shell is based on similarities with the irregular arc that is bright in [O III]. More specifically, the morphology, orientation, and thickness of the emission are nearly identical to the closer irregular arc already identified as a nova shell. The lack of [O III] emission is not surprising given the fact that the [O III] flux of nova shells decreases faster than H $\alpha$  (Tappert et al. 2020). Moreover, both in our H $\alpha$  imaging as well as in other H $\alpha$  surveys (Parker et al. 2005), no similar half-rings are present in the nearby H II region. Hence, we conclude that the  $\sim 4'$  half-ring may be an even older nova shell of RX Pup. However, we note that further observations are needed for a conclusive identification.

### 3.1. The Nova Shells' Properties

The fact that the nova remnants are observed mainly east of RX Pup is consistent with observations from the 1970s outburst, where the material ejected during the nova seemed to move in an eastern direction from RX Pup (Hollis et al. 1989). Moreover, it is possible that the nova shells west of RX Pup are hidden behind the nearby H II region. Another possibility is fast deceleration of nova shells due to collision with the H II region west of RX Pup. In fact, the RX Pup distance of  $\sim 1.6$  kpc (Gromadzki et al. 2009) is similar to a possible distance of the H II region of 1.4–1.6 kpc (Chen et al. 2019), making this a possibility. On the other hand the

emission arc is not a bow shock created due to the proper motion of RX Pup, as its proper motion is toward the northwest direction (Gaia Collaboration et al. 2021). Asymmetric multi-shell structures are observed in several other symbiotic postnovae and SySts with Mira donors (e.g., Corradi 2003; Bujarrabal et al. 2018); however, in the case of RX Pup the interpretation is more demanding due to the nearby H II region.

In order to date the nova shells around RX Pup we employed archival observations from the SuperCOSMOS H $\alpha$  survey (Parker et al. 2005). This image of RX Pup was carried out on 1998 January 29, 18.85 yr before our Swope images. We revised the astrometric solution of the SuperCOSMOS image in the same way that we obtained the astrometric solution for our Swope image. On the SuperCOSMOS image the irregular arc east of RX Pup is clearly visible, while we did not detect the  $\sim 4'$  half-ring due to its lower relative brightness. Visual inspection of the two images showed expansion of the nova shell (Figure 4). The distance of the irregular arc from RX Pup on both the SuperCOSMOS and Swope images was measured in 10 different directions, ranging in positional angles from  $45^\circ$  to  $90^\circ$ . The positional angles were chosen to avoid blending with background stars and diffraction spikes on the SuperCOSMOS image. The distances between RX Pup and the nova shell were measured by extracting the flux along a line at the direction of the chosen positional angle, fitting a Gauss function to the emission from the nova shell and extracting the position of the Gauss function maximum. As a result we measured that the nova shell expanded on average by  $0''.65 \pm 0''.16$  in 18.85 yr and the average expansion rate by  $34.5 \pm 8.5$  mas yr $^{-1}$ . At the distance of RX Pup this corresponds to an expansion velocity of  $262 \pm 65$  km s $^{-1}$ . This is consistent with the lower limit of the 1970s nova shell expansion velocity of  $80$  km s $^{-1}$  (Corradi & Schwarz 2000) and nova shell expansion velocities in other objects (Santamaría et al. 2020).

The average radial velocities of emission lines from the irregular arc (Table 1) are consistent with the radial velocity of RX Pup ( $\sim 20$  km s $^{-1}$ ) as well as with the Galactic rotation velocity at the position and distance of RX Pup

(Mikołajewska et al. 1999; Corradi & Schwarz 2000). The radial velocities vary between regions similarly to what is observed in other SySts with outflows (Santander-García et al. 2008). The radial velocities observed in regions B2, C3, and D3 ( $-5$  to  $-17$  km s $^{-1}$ ) are between the radial velocities of the irregular arc and the material ejected by the 1970s nova in the same eastern direction ( $-80$  km s $^{-1}$ ; Corradi & Schwarz 2000). While they are too far away from the system ( $14''$ – $28''$ ) to be associated with the 1970s outburst they may originate from yet another outburst.

The irregular shapes of nova shells around RX Pup hinder determination of its age. Hence, for consistency we use their sizes at a positional angle of  $94^\circ$ , where both the smaller irregular arc and the larger  $\sim 4'$  half-ring have similar morphology and width. This gives us their sizes of  $43''.30 \pm 0''.10$  and  $239''.94 \pm 0''.55$ , respectively. Assuming a constant expansion velocity of  $34.5 \pm 8.5$  mas yr $^{-1}$  this corresponds to ages of  $\sim 1300$  and  $\sim 7000$  yr, if the  $\sim 4'$  half-ring is assumed to be a nova shell. We note that the material ejected in an eastern direction from RX Pup during its last outburst expanded by  $0''.39$  in  $\sim 10$  yr (Hollis et al. 1989). The resulting average expansion rate of  $\sim 39$  mas yr $^{-1}$  is practically the same as we have measured for the inner smaller irregular arc, which indicates that the shell slowed down shortly after ejection as expected for the swept-up wind material. Moreover, the compatibility of both estimates implies that the shells remain in the free expansion phase for at least  $\sim 1000$  yr. This is consistent with the observed CN shells that show constant expansion velocities for at least the first century after the outburst (Santamaría et al. 2020; Celedón et al. 2024), even when strong interaction between the nova ejecta and interstellar medium is present (Liimets et al. 2012; Shara et al. 2012; Harvey et al. 2016).

#### 4. Conclusions

In this work we reported the discovery of a  $\sim 1300$  yr old nova shell forming an irregular arc around RX Pup. Additionally, we identified a possible  $\sim 7000$  yr nova shell appearing as a  $\sim 4'$  half-ring. Together with the 1970s outburst this implies a change of nova recurrence time from  $\sim 5700$  to  $\sim 1250$  yr assuming a constant expansion rate. A long timescale and low luminosity of the last outburst of RX Pup suggest a WD mass in the range of  $0.6$ – $0.8 M_\odot$  (Mikołajewska et al. 1999; Mikołajewska 2010). If we assume typical values of a mass of the WD  $M_{\text{WD}} = 0.65 M_\odot$  and a temperature of its isothermal core  $T_{\text{WD}} = 30 \times 10^6$  K, a change of mass transfer

rate can be estimated by interpolating the theoretical CN models of Yaron et al. (2005). This approach suggests that a change in the recurrence time of nova outbursts from  $\sim 5700$  to  $\sim 1250$  yr for the assumed WD parameters is due to a change of the average mass transfer rate from  $\sim 2.8 \times 10^{-8} M_\odot \text{ yr}^{-1}$  to  $\sim 7.9 \times 10^{-8} M_\odot \text{ yr}^{-1}$ . Hence, the mass transfer rate in RX Pup increased by roughly a factor of 3. Since the WD had to accumulate mass on its surface before the outburst that occurred  $\sim 7000$  yr ago, this means that the measured change in mass transfer rate occurred on a timescale of roughly  $10,000$  yr. Moreover, regions C3 and D3 (Figure 2) are not visible in our imaging, but their spectra suggest that they may originate from yet another outburst. If confirmed, this would suggest that the mass transfer rate evolution in RX Pup was faster than we estimated.

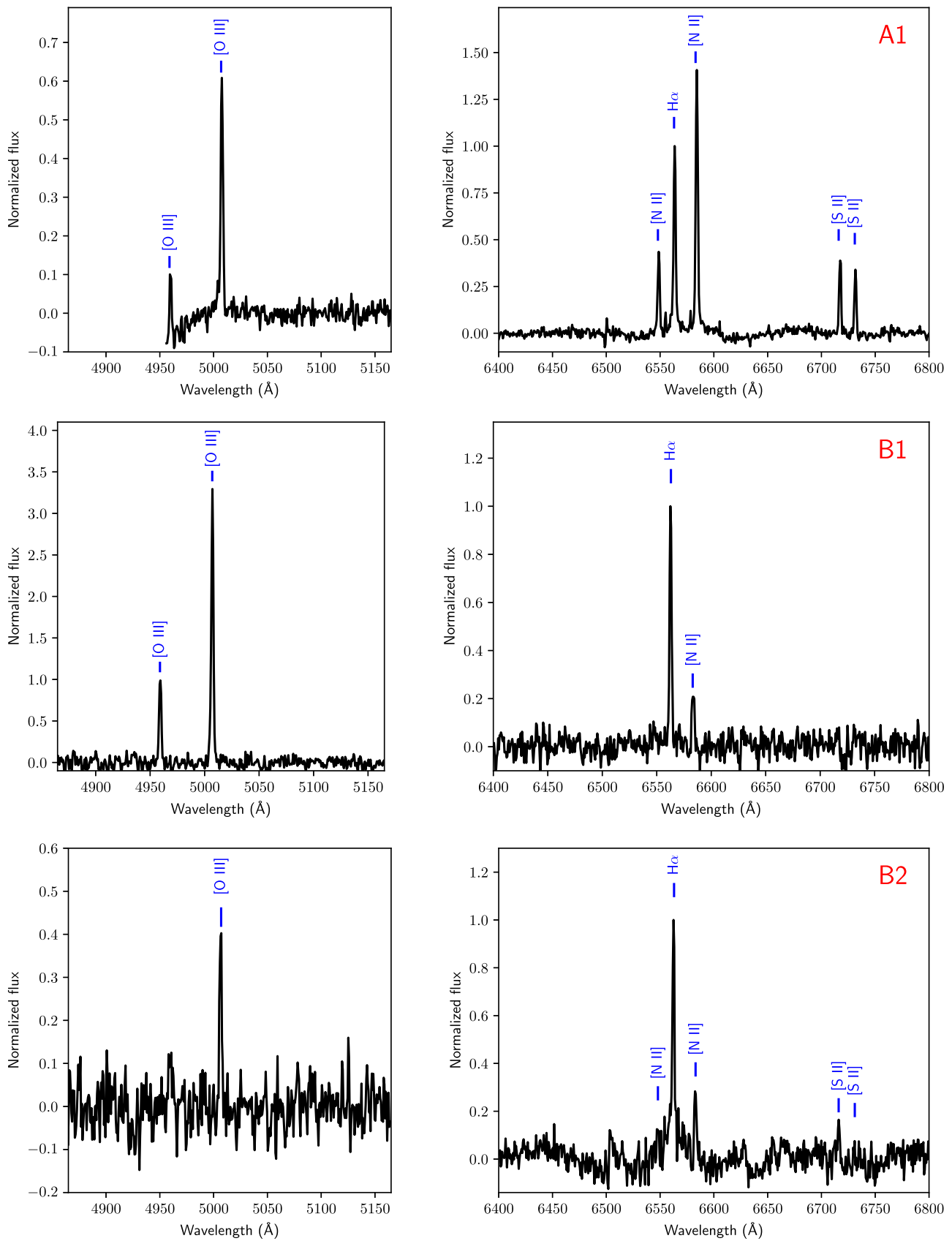
The change of mass transfer rate is the first measurement of variable mass transfer rate in binary stars on timescales of millennia. This result is consistent with the evolutionary status of the Mira in RX Pup implied by its dust obscuration events (Mikołajewska et al. 2001). Namely, single stars similar to the mass donor in RX Pup experience variable mass loss on similar timescales (Zijlstra et al. 2002). Hence, RX Pup may serve as a laboratory of how the evolution of the mass donor influences the mass transfer rate in binary stars with wind accretion. This is particularly interesting given that such binaries have been suggested as promising supernova Ia candidates (Hkiewicz et al. 2019a).

#### Acknowledgments

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#### Appendix

All of the spectra used in this work are presented in Figure 5. The log of spectroscopic observations is presented in Table 2.



**Figure 5.** Spectra of different nova shell regions in the H $\alpha$  and [O III] regions with names of regions given with a red text (see Figure 2). The flux was normalized to the H $\alpha$  maximum flux.

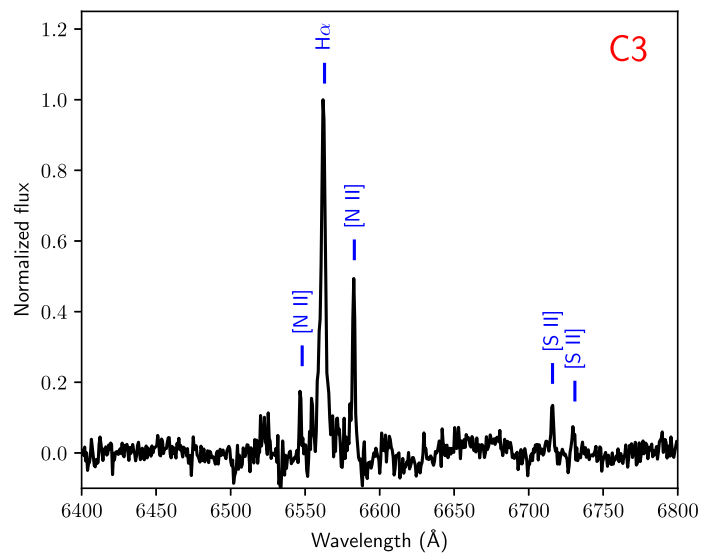
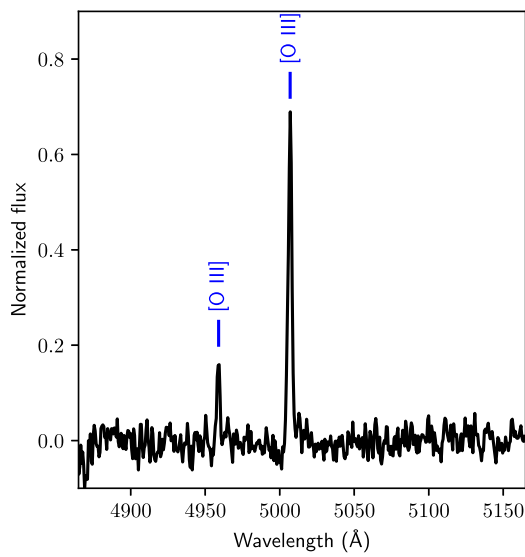
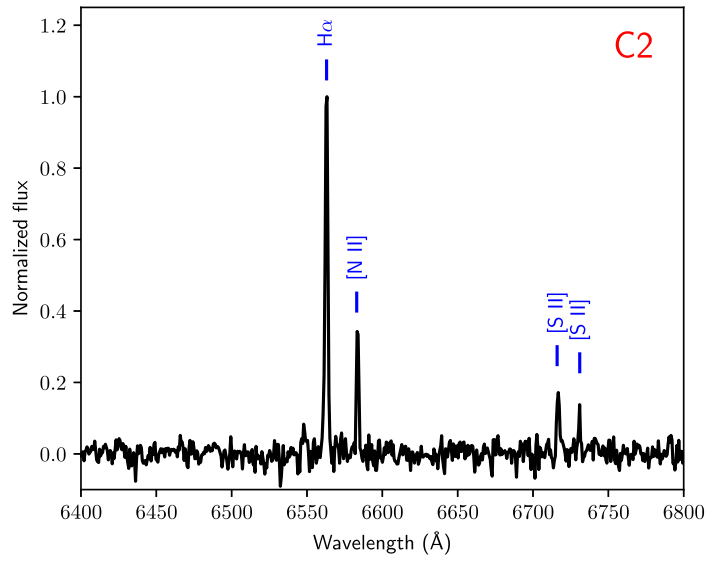
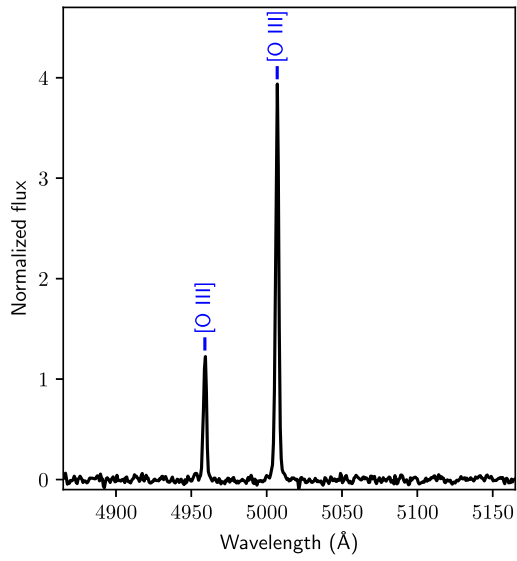
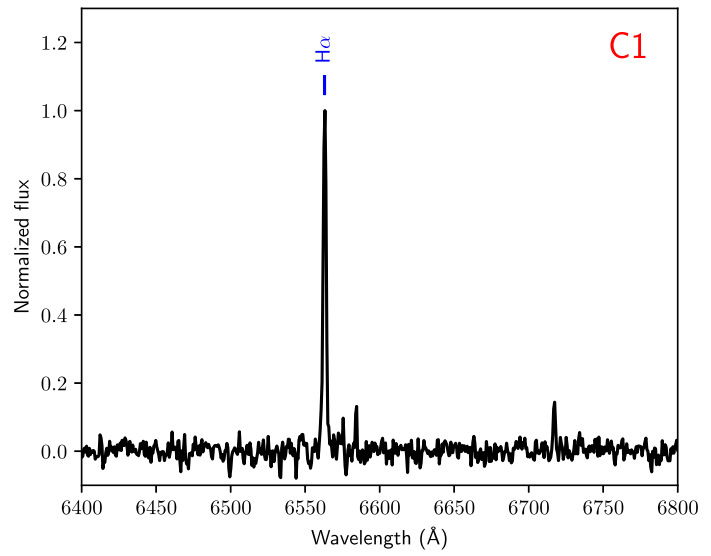
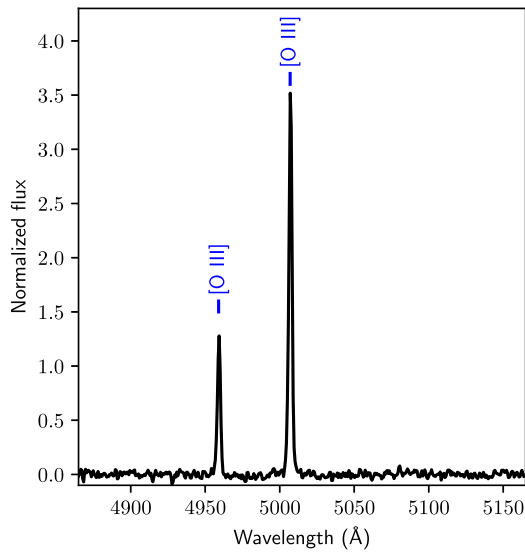


Figure 5. (Continued.)



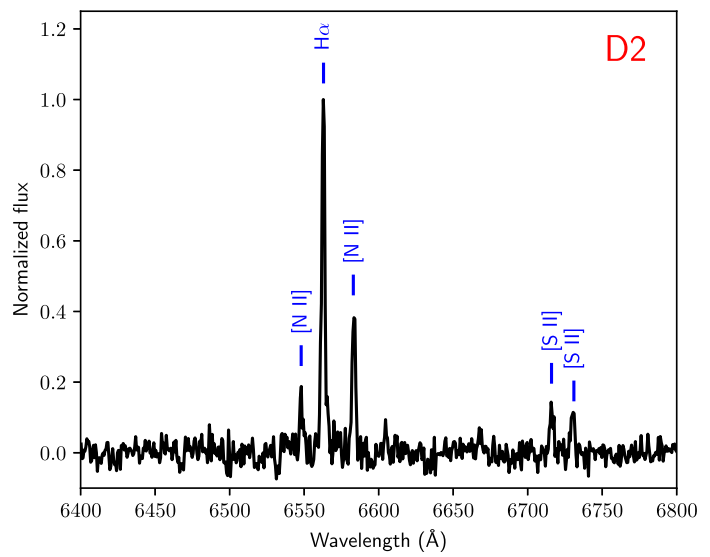
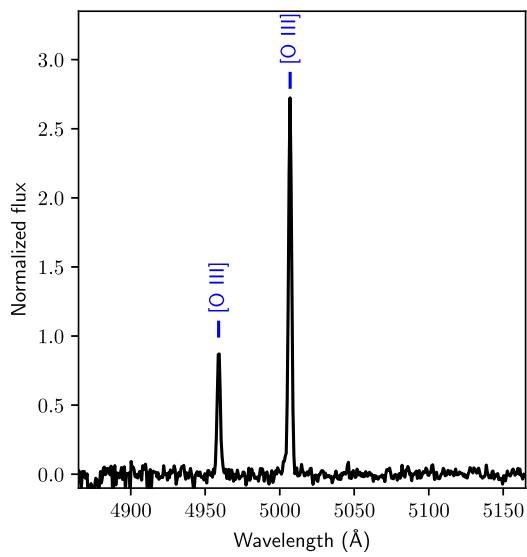
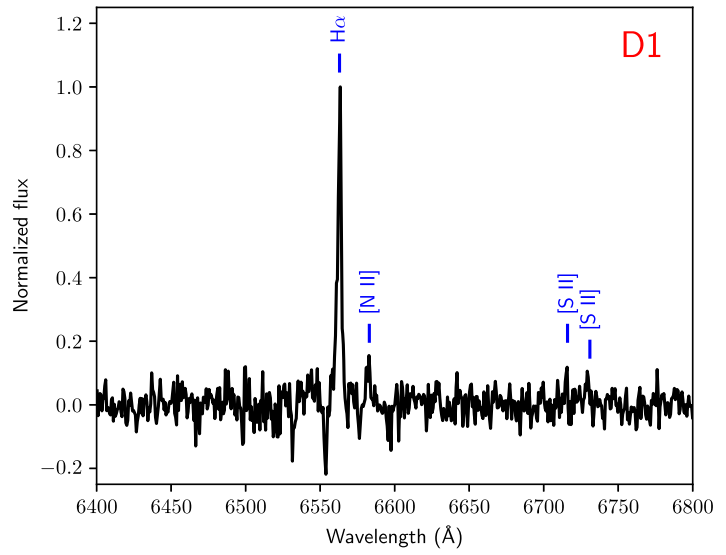
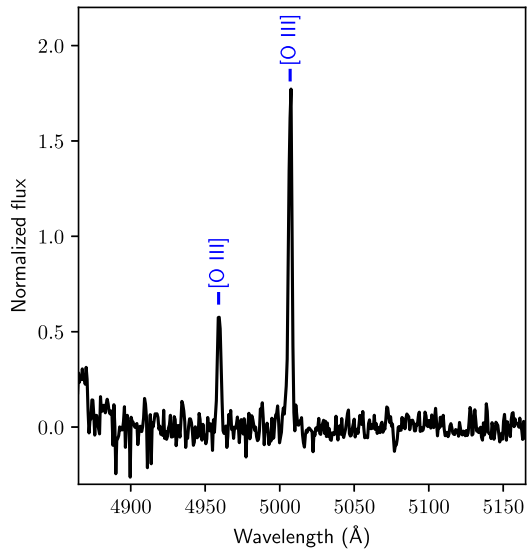
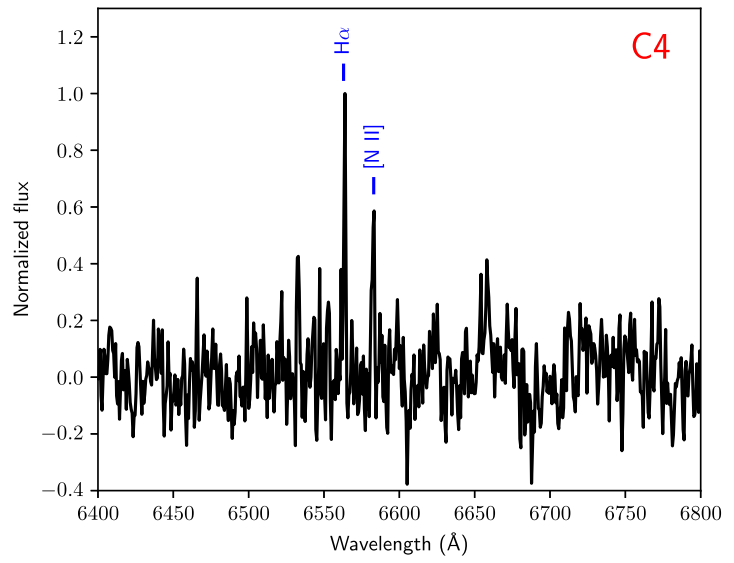
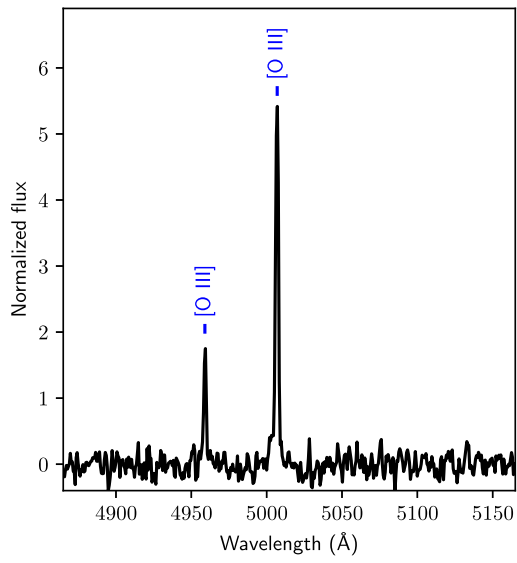


Figure 5. (Continued.)

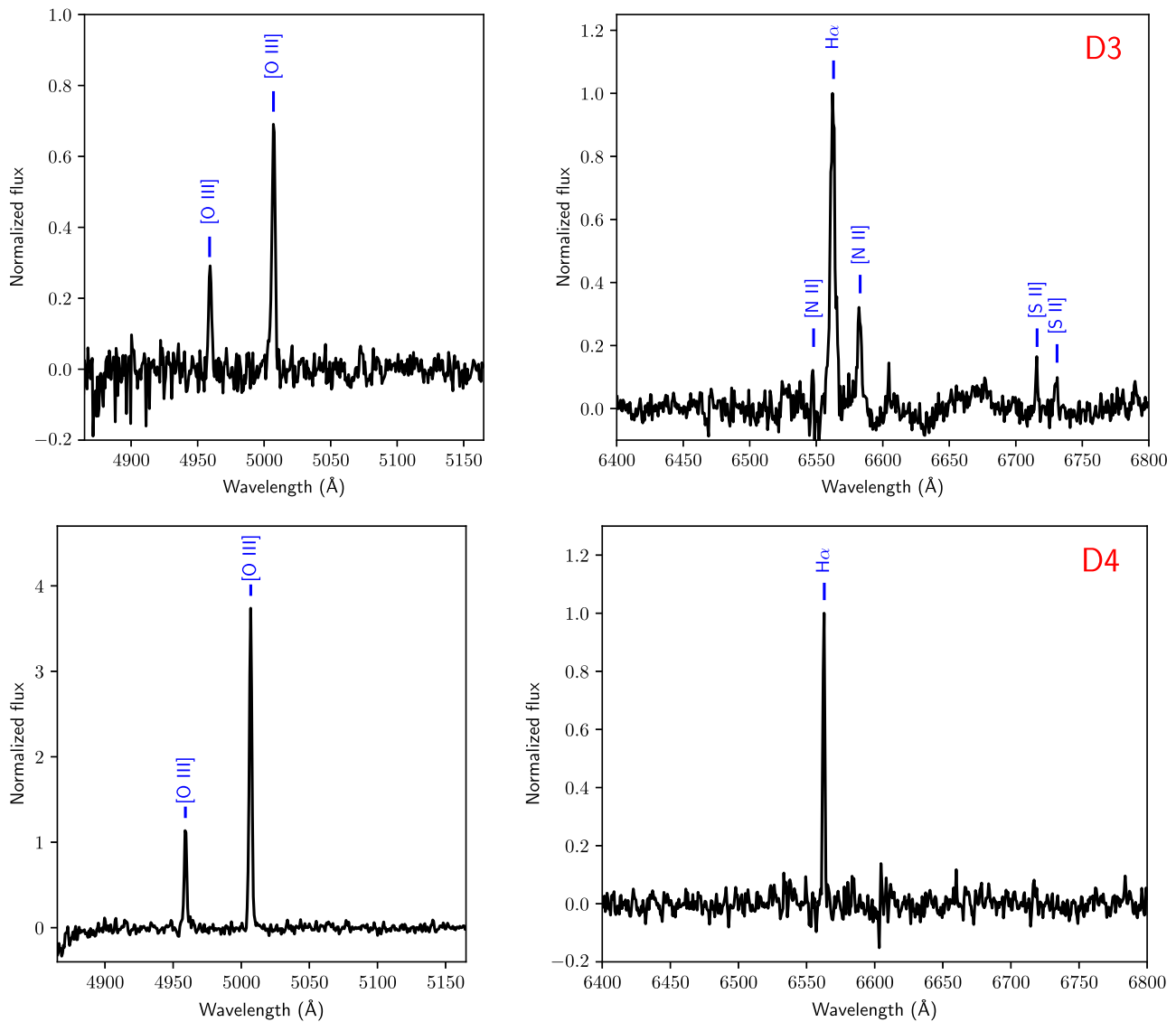


Figure 5. (Continued.)

Table 2

Log of Spectroscopic Observations at Different Slit Positions (See Figure 2)

Slit Position	Date	JD	Exposure Time (s)
A	2019-11-02	2458789.5	2510
B	2019-10-05	2458761.6	2400
C	2019-11-04	2458791.5	2510
D	2019-11-03	2458790.5	2510

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