Infrared spectroscopy of the remnant of Nova Sco 2014: a symbiotic star with too little circumstellar matter to decelerate the ejecta

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ABSTRACT

Pre-outburst 2MASS and WISE photometry of Nova Sco 2014 (V1534 Sco) have suggested the presence of a cool giant at the location of the nova in the sky. The spectral evolution recorded for the nova did not however support a direct partnership because no flash-ionized wind and no deceleration of the ejecta were observed, contrary to the behavior displayed by other novae that erupted within symbiotic binaries like V407 Cyg or RS Oph. We have therefore obtained an 0.8–2.5 μm spectra of the remnant of Nova Sco 2014 in order to ascertain if a cool giant is indeed present and if it is physically associated with the nova. The spectrum shows the presence of a M6III giant, reddened by E(B-V)=1.20, displaying the typical and narrow emission-line spectrum of a symbiotic star, including HeI 1.0830 μm with a deep P-Cyg profile. This makes Nova Sco 2014 a new member of the exclusive club of novae that erupt within a symbiotic binary. Nova Sco 2014 shows that a nova erupting within a symbiotic binary does not always come with a deceleration of the ejecta, contrary to the common belief. Many other similar systems may lay hidden in past novae, especially in those that erupted prior to the release of the 2MASS all-sky infrared survey, which could be profitably cross-matched now against them.

Key words: novae, cataclysmic variables

1 INTRODUCTION

Classical novae (CNe) are compact binary systems, where mass is transferred to a white dwarf (WD) - usually via the L1 Lagrange point - from a compact, low-mass and lower-main sequence companion (see Bode & Evans 2012 and Woudt & Ribeiro 2014 for recent reviews). The electron degenerate envelope accreted on the surface of the WD on reaching critical conditions for ignition undergoes a thermonuclear runaway (TNR) that leads to violent mass ejection into the surrounding empty space. Once it is launched, the ejected material keeps expanding at about constant velocity, with the short orbital separation between components of the system being covered very quickly after the TNR. The orbital distance of CNe is of the order of ~1 solar radius and the ejecta, travelling at a typical velocity of ~1000 km/s, traverses it in the initial 10-15 minutes. At this stage the ejecta is akin to an extremely hot fireball which is still a few days ahead of the phase when the nova will be discovered at optical wavelengths and/or will reach maximum brightness. For weeks around maximum brightness (basically until the ejecta remains optically thick), only gradual and limited changes affect the profile shapes and radial velocity of the emission lines and the P-Cyg absorptions that flank them. Under assumptions of spherical symmetry for the ejecta of CNe, these changes can be related to the ionization/recombination front propagating through the ejecta as it keeps diluting. In a multi-component model for the ejecta (e.g., a faster bipolar flow along the orbital axis and a slower toroidal expansion on the equatorial plane), the picture grows more complex as considerations of the viewing angle, actual geometrical shapes and different velocities and densities for the components have to be taken into account.

In a minority of novae (a few % of the total), the spectral changes around maximum brightness can however be fairly dramatic which are manifested on a time scale of hours to a few days. These novae erupt within pre-existing symbiotic binaries (hereafter termed for convenience as NwSS for "Nova within a Symbiotic System"), where the WD orbits a late-type, cool giant star. Such NwSS tend to be recurrent by virtue of the high mass of the WD and the high mass-transfer rate from the giant. The size of the latter sets the typical orbital period and separation between components
to be \(\sim 2\) years and \(\sim 2\) AU, respectively. It would take \(\sim 100\) hours for the ejecta freely expanding at 1000 km/s to cover such a distance, so the very large companion to the erupting WD may not be engulfed by the expanding ejecta for some time around optical maximum. Cool giants lose matter into circumstellar space at a high rate through sustained stellar winds, and it is this wind that is at the origin of the spectacular spectral changes that affect NwSS\(^[1]\). The outburst of RS Oph in 2006 (e.g. Evans et al. 2008, Das et al. 2006) and V407 Cyg in 2010 (e.g. Munari et al. 2011) are template cases. The powerful initial UV-flash accompanying the TNR onset goes undetected by observers and is lost into surrounding emptiness in the case of classical novae whereas in the NwSS it ionizes the circumstellar gas originating from the wind of the giant. The resulting radiation from the recombining flash-ionized gas is so intense that the NwSS is brought from quiescence to maximum brightness in a very short time which is essentially the light-travel time through the circumstellar gas.

The spectrum of the flash-ionized gas comprises of a forest of emission lines, some emanating from atoms at high degrees of ionization, which are quite narrow in width because the circumstellar gas originates from a low velocity stellar wind from a giant (expansion velocity typically \(\sim 10\) km/s). The electron density of the wind material is high enough \((n_e \sim 10^9/10^7 \text{ cm}^{-3})\) for the recombination timescale to be of the order of a few days. While these narrow lines weaken, much wider lines begin to emerge beneath them as the result of the fast expanding ejecta of the nova. While these latter lines grow in prominence, their FWHM however decline as a consequence of the ejecta being slowed down while trying to expand through the surrounding medium. As an example, during the 2010 outburst of the NwSS V407 Cyg, Munari et al. (2011a) measured e-folding times of 4 days for the recombinant of the flash-ionized gas and of 3 days for the deceleration of the ejecta.

V1534 Sco (= Nova Sco 2014) was discovered on 2014 Mar 26.85 by K. Nishiyama and F. Kabashima (CBET 3841). Spectroscopic classification as an He/N nova was obtained on Mar 27.8 by Ayani & Maeno (2014), who reported a FWHM of 7000 km/s for the H\(\alpha\) line. Joshi et al. (2015, hereafter J2015) studied the nova using near-IR spectroscopy covering the first 19 days of the outburst. Their near-IR spectra confirmed an He/N classification, with emission lines characterized by a wide trapezoidal shape with a narrow component sitting on the top. The positional coincidence with a bright 2MASS cool source with an H\(\alpha\) excess and the presence of first overtone absorption bands of CO at 2.29 microns (as seen in M type stars) led J2015 to suggest that V1534 Sco was a new member of the exclusive NwSS club. Initial X-ray observations obtained by Kuulkers et al. (2014) and Page, Osborne and Kuulkers (2014), seemed to support the NwSS scenario, being consistent with a shock emerging from the wind of the secondary star. Also the accurate optical lightcurve presented by Munari et al. (2017) could be interpreted (not unequivocally though) as the superposition of a recombining flash-wind and an expanding ejecta.

There was however one aspect seen in V1534 Sco that conflicted with a NwSS interpretation for it viz. the sequence of near-IR spectra presented by J2015 showed emission lines of near constant width which did not undergo the rapid shrinking in velocity expected with the deceleration of the ejecta expanding through the pre-existing wind of the M-giant companion. In addition to this, it may also be mentioned that no \(\gamma\)-ray emission was reported for V1534 Sco, whereas such emission may have been expected to arise from shocks associated with the high-velocity ejecta ramming into the wind of the M-giant, as observed in other NwSS (Ackermann et al. 2014). Furthermore, it will be shown below by re-analyzing some of the J2015 near-IR spectra, that no flash-ionized wind was initially present in V1534 Sco. It was as if V1534 Sco hosted a cool giant but lacked the extended circumstellar material that normally surrounds it.

In order to clarify its true nature, we have recently obtained a near-IR spectrum of the remnant of V1534 Sco, aiming to answer two basic questions: (a) is the bright 2MASS sources noted by J2015 indeed a cool giant, and if yes (b) is it physically associated with V1534 Sco or it is just an unrelated object that happens to lie along the same line of sight to the nova. Exploring these aspects will lead to a redefinition of the so far widely accepted paradigm about a nova erupting within a symbiotic binary.

2 OBSERVATIONS

V1534 Sco was observed with the SpeX spectrograph (Rayner et al. 2003) on the 3m NASA Infra-Red Telescope Facility (IRTF), Hawaii, on 2017 February 17.63 UT. SpeX was used in the cross-dispersed mode using a 0.5”x15” slit resulting in a spectral coverage of the 0.77-2.50 micron region at resolving power of 1200. The total integration time was 319 seconds. The AOV star HIP 86098 was used as the telluric standard. The data were reduced and calibrated using the SPEXTOOL software (Cushing et al. 2004) and corrections for telluric absorption were performed using the IDL tool XTELLCOR (Vacca et al. 2003). The IRTF spectrum of V1534 Sco is presented in Figure 1, colored in black.

3 AN M6III SYMBIOTIC BINARY

3.1 Spectral type and reddening

The NIR spectrum of V1534 Sco in Figure 1 presents strong molecular bands, from TiO at \(\lambda \geq 1.0\) \(\mu\text{m}\) and CO for \(\lambda \geq 2.3\) \(\mu\text{m}\), typical of M-type giants. In order to derive the spectral type and luminosity class, and measure the interstellar reddening, we have carried out an extensive \(\chi^2\) fit against the whole IRTF library for M-type stars (Cushing, Rayner, & Vacca 2005; Rayner, Cushing, & Vacca 2009), exploring the
The IRTF-SpeX spectrum of V1534 Sco for 16 Feb 2017 is nearly perfectly fitted with that of an M6III template reddened by $E(B-V)=1.2$ following the standard $R_V=3.1$ law as tabulated by Fitzpatrick (1999). The M6III template (HD 196610) is taken from the IRTF-SpeX spectral atlas of M stars (Cushing, Rayner, & Vacca 2005; Rayner, Cushing, & Vacca 2009).

The best fit was found with the M6III star HD 196610, reddened by $E(B-V)=1.20$, which is plotted in red in Figure 1. The match is strikingly good over the whole wavelength range and it is quite hard to distinguish between the observed V1534 Sco spectrum and the reddened M6III spectrum. The first overtone $^{13}$CO absorption bands are present in V1534 Sco along the corresponding $^{12}$CO sequence over the 2.3–2.5 μm spectral region, with an intensity suggesting a ratio $^{12}$C/$^{13}$C~10. A more accurate estimate would require a full model atmosphere analysis (vastly outside the scope of the present paper) which could also derive chemical abundances essential to evaluate if the giant is on the RGB or on the AGB (eg Pavlenko et al. 2003, 2008).

In principle, while modelling the SED, a cooler M-type could be traded off for a lower reddening, and vice-versa. This is a major risk specifically when only broad-band photometric data or a featureless continuum are available for the SED modelling, as demonstrated by the different fits that J2015 and Munari et al. (2017) performed to available BVRI/JHK/Wise photometry of the progenitor of V1534 Sco. The degeneracy between intrinsic energy distribution and reddening is removed in the present case by the presence of molecular bands in the spectra of V1534 Sco. Their depth is invariant with reddening but a strong function of spectral type, particularly for TiO (e.g. Kenyon & Fernandez-Castro 1987). As illustrated in the top panel of Figure 2, there is a good match in the depth of TiO bands between the template M6III star and V1534 Sco. The depth of the TiO bands for M5III and M7III template stars would under-fit and over-fit, respectively, those seen in V1534 Sco, no matter what value of the intervening reddening is considered. Once the spectral type is fixed, the overall shape and curvature of the spectral energy distribution returns the reddening.

The formal errors of the $\chi^2$ fit are rather low: less than 0.3 spectral subtypes and just 0.02 mag in the reddening.

They would increase by incorporating the (not easily quantifiable) uncertainties attached to the flux calibration of the IRTF spectral library and the present spectrum of V1534 Sco, and to the Fitzpatrick (1999) reddening law.

### 3.2 The emission line spectrum

There are several emission lines visible in the IRTF spectrum of V1534 Sco, as illustrated in the zoomed views of Figures 2, 3, and 4.

Figure 2 focuses on the 0.84–0.94 μm region. The OI 0.8446 μm emission line is already evident in the direct spec-
Figure 3. Comparing the blue end of the IRTF spectrum with that of the M6III symbiotic star Hen 3-1410 taken from the spectral atlas of symbiotic stars by Munari & Zwitter (2002).

Figure 4. Similar to Figure 2, the upper panel shows an expanded view from Figure 1, this time around the HeI 1.0830 µm line, while the central panel presents the result of the subtraction of the M6III spectrum from that of V1534 Sco. Note the presence of a deep P-Cyg absorption component for the strong HeI line. For comparison a spectrum of T CrB, an M3III symbiotic star and recurrent nova, taken on the same night as V1534 Sco, is also shown (its flux divided by 100 to fit the scale).

The spectral region explored in more detail in Figure 4 is that of HeI 1.0830, Paschen-γ 1.0938 and OI 1.1287 µm which are clearly present in emission in the spectrum of V1534 Sco. They well match what is normally seen in symbiotic binaries, as proved by the comparison with T CrB in the bottom panel of Figure 4 (this IRTF spectrum of T CrB - itself a NwSS - was taken on the same night and with the same instrumental set-up of V1534 Sco). The only significant difference between T CrB and V1534 Sco is the deep P-Cyg absorption that the latter displays for HeI 1.0830 µm. It is not an observational artifact and there is no photospheric line at this position that could mimic such a P-Cyg profile, as proved by the over-plotted spectrum for the M6III template. P-Cyg profiles are sometimes observed for HeI lines in symbiotic stars (e.g. Smith 1981), their presence and intensity being usually a function of orbital phase (e.g. Munari 1993).

The emission lines seen in V1534 Sco are all narrow and thus incompatible with an origin in the greatly diluted ejecta of the nova. The presence of a strong P-Cyg absorption for HeI 1.0830 µm requires a high column density, again incompatible with a diluted nova ejecta. The emission lines are therefore physically associated with the stellar system containing the M6III giant, making it a symbiotic binary. It is highly improbable that the symbiotic binary and the nova are unrelated and seen just by chance along the same line of sight. We therefore conclude that Nova Sco 2014 erupted from the symbiotic binary V1534 Sco, making it a new member of the exclusive club of NwSS, which currently counts about a dozen recognized members.

4 NO FLASH-IONIZED WIND OR DECELERATING EJECTA

The absence of deceleration of the ejecta in Nova Sco 2014 was already noted by J2015, but they did not elaborate further on this and the narrow emission peak seen sitting on top of the broad emission lines. We will have a closer look to them in this section, starting from the same near-IR spectra of Nova Sco 2014 as presented by J2015.

The profiles of the HeI 1.0830 µm emission line of Nova Sco 2014 are shown in Figure 5, as illustrative of similar profiles affecting the other emission lines seen in the J2015 spectra. The two components, a broad trapezoidal pedestal and a narrow Gaussian central peak, are quite obvious. We have measured from these profiles the FWHM and the integrated fluxes of both components, with the results plotted in Figures 6 and 7.

The broad component slowly declines in width, with an e-folding time of months instead of days as for other NwSS. This slight reduction in width is far too slow for a deceleration caused by the ejecta ramming into any circumstellar material. It is instead in line with what is usually observed in classical novae, for which ejecta freely expand into the surrounding empty space. This is because the recombina-
Evolution of the profile for HeI 1.0830 μm during the 2014 nova outburst of V1534 Sco, to highlight the narrow component and the broad pedestal. From Joshi et al. (2015) spectral data.

The narrow component presents in Figure 6 a stable FWHM around ~600 km/sec, or about one and half times the instrumental resolving power of ~400 km/sec in the J band. This would prove that it cannot originate in the quiet wind of the cool giant flash-ionized by the initial nova TNR. Also the evolution of its flux in Figure 7, is far removed from the fast decline in strength associated with the rapid recombination seen in NwSS which is completed in a matter of a few days. Instead what is seen here is an initial constant flux lasting about a week, then a slow decline in line with the expectation from a thinning and diluting ejecta. The narrow component sitting on top of the broad trapezoidal pedestal closely resembles the similar structural arrangement as seen in another He/N nova, V2672 Oph (Nova Oph 2009), for which morpho-kinematical modelling (Munari et al. 2011b) indicated in a higher density, slow-expanding equatorial torus in the ejecta the location which produced the narrow component. It is quite possible that the formation rate in the ejecta, and therefore the contribution to the emission, is proportional to the local electron density. The latter declines quicker in the outer and faster expanding ejecta, reducing their relative contribution to the overall line profile which therefore appears to be narrowing (e.g. Munari et al. 2011b). This interpretation is reinforced by noting in Figure 7 how the evolution of the integrated flux of the broad component is rapidly seen approaching the \( t^{-3} \) slope of a recombining, optically thin gas.
Nova Sco 2014 shares a similar bipolar morphological structure as V2672 Oph.

From the lack of evidence for a flash-ionized wind and also lack of evidence for deceleration of the nova ejecta, we conclude that the M6III giant in V1534 Sco is inefficient in engulfing its orbiting WD companion with a wind of any significance.

5 A REVISED PARADIGM FOR A NOVA WITHIN A SYMBIOTIC BINARY SYSTEM

We have been used to the notion that a nova erupting within a symbiotic binary should inevitably face the consequences of its extended circumstellar material viz. a rapid and striking deceleration of the ejecta (e.g. Munari et al. 2011a for V407 Cyg, Das et al. 2006 for RS Oph; Banerjee et al. 2014 for V745 Sco; Srivastava et al. 2015 for Nova Sco 2015).

V1534 Sco has proved that this is not always the case. Looking closer, we may even find examples of transitional cases, like Nova Oph 2015 (Munari & Walter 2016) thereby showing a diversity characterised by the examples below:

Nova Sco 2014: no flash-ionized wind and no deceleration of the ejecta.
Nova Oph 2015: modest amount of flash-ionized wind; mild deceleration of the ejecta which after a short time breaks free of the wind and then continues on a free expansion.
V407 Cyg: huge amount of flash-ionized wind; prolonged and complete deceleration of the nova ejecta.

If we leave aside any complication associated with the viewing angle in a non-spherical morphology for the ejecta, the governing factor for such different behavior seems to be the amount of matter shed by the cool giant into the immediate circumstellar environment within which the WD companion orbits.

We argue that multiple causes may lead to such differences (which may reverse with time depending on distinct episodes of enhanced mass-loss, eg. Baade & Reimers 2007), including metallicity, dust grain formation, surface gravity, degree of Roche-lobe filling by the cool giant and amount of irradiation by the WD companion. They can alter by ample proportion the fraction of mass lost to the circumstellar space via wind compared to that funneled through L1 directly toward the accreting companion.

We note that other symbiotic stars may lay hidden in past novae. The symbiotic star in V1534 Sco would have remained undiscovered if the spatial coincidence with a bright 2MASS source went unnoticed and if the post-outburst observations described in this paper would not have been performed. No spatial coincidence with bright IR sources was normally carried out for novae that erupted before the release of the 2MASS survey. Doing it now could pay some dividends and promote observations of the remnants similar to those presented here.

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