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High-angular-resolution studies of symbiotic novae

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Abstract. Novae stars have fascinated observers around the world for centuries. They are eruptive close binary stellar systems consisting of a white dwarf and a secondary stellar component, which in rare cases is a red giant. Such systems are called symbiotic novae. Since the nova phenomenon is unexpected in most cases, there is a lack of observations and understanding, especially of the very early phases of their eruptions. To resolve and understand these early epochs, very fast and exceptionally high-angular-resolution methods of observations are needed. Symbiotic novae are the right systems for studies in the infrared, thus the optical interferometry is the ideal solution in this case. We discuss three of them, namely RS Oph, V3890 Sgr, and T CrB.

Key words: binaries – close binaries – cataclysmic stars – symbiotic stars – novae – optical interferometry – high-angular-resolution – RS Oph – V3890 Sgr – T CrB

1. Introduction to novae and motivation

Novae have been one of the most intriguing objects in the sky since the early days of astronomy. These unexpected, sudden, and relatively short increases in brightness attract the attention of astronomers and fascinate observers. The nature of a nova phenomenon has been a mystery for many centuries until very recently.

Walker (1954) first showed that a famous nova DQ Herculis is in fact a short-period binary system. This was a breakthrough discovery raising the question of whether all novae are binaries. Later, spectroscopic observations confirmed this hypothesis for these objects (Greenstein & Kraft, 1959). Next, the same conclusion was drawn for dwarf novae by Kraft (1962), who introduced a binary star model of such stars, where the cool star fills its Roche lobe and transfers matter to the hot companion star through a disk-like structure.

Then the whole standard model of a cataclysmic system developed during the next years. Krzeminski & Kraft (1964) introduced a stream in the binary model of WZ Sge, while Warner & Nather (1971) and Smak (1971), based on observations of another dwarf nova, U Gem, discussed the nature of the hot spot. Walker & Chincarini (1968) interpreted the hot stellar component as the origin of the outbursts, in contrast to the previous conclusions of Krzeminski (1965), which allowed the proper theoretical work to begin (Paczyński, 1971). All these discoveries, dating back only ~ 50 years, allowed us to slowly begin to understand the nature of cataclysmic variables (CV) in general and novae in particular (Robinson, 1976; Patterson, 1984).

Although our understanding of novae is not yet complete, the standard CV model that evolved over the years is supported by the observational data that are constantly flowing to us. We now know that novae are semi-detached binary stellar systems which erupt. Such an explosion of a nova occurs on the surface of the hot stellar component, i.e. a white dwarf (WD), while the secondary is a less evolved star, typically a main-sequence (MS) object or a red giant (RG). The secondary is a donor star as it fills the Roche lobe and loses material to its companion. This transported matter forms an accretion disc around the WD and gradually falls to its surface. Thus, WD slowly gains mass. At critical mass the matter becomes degenerate and a thermonuclear runaway (TNR) starts (Warner, 1995). Up to 10^{-4} $M_{\odot}$ of the material is removed from the system (Chomiuk et al., 2021) at speeds of hundreds or even thousands of kilometers per second.

Some time after the explosion the whole system returns to the state of active accretion and another accumulation of matter, until the next eruption. The entire cycle repeats with recurrence time depending on the mass accretion rate and the mass of the WD (Shara et al., 2018). So, the recurrence times differ significantly between diverse systems. In the case of classical novae (CN), these are times of the order of thousands of years (Shara et al., 2012).

If a system recur on timescales of the order of at most hundreds of years, it is called a *recurrent* nova (RN). Such binaries are rare, since we know only 10 RN in our Galaxy. RN systems containing a red giant as a donor star are known as *symbiotic recurrent novae* (SyRN). They are even rarer (4/10 of the known Galactic RN), namely: T CrB, V745 Sco, RS Oph, and V3890 Sgr. The surroundings of SyRN are complex, because in addition to both the stellar components, they may include additional gas and dust. What is more, a circumbinary, possibly spiral structures in the binary orbital plane as well as stellar wind effects must be also taken into account (Mohamed & Podsiadlowski, 2012).

Recently, a number of very interesting and important discoveries have been made, significantly expanding our knowledge about novae. Among others, e.g. the works on shocks of the ejecta (H. E. S. S. Collaboration et al., 2022) or gamma ray emission (Acciari et al., 2022), strong X-ray emission (Ness et al., 2023), coronal line emission in the UV, optical and IR, and others (Molaro et al., 2023). Although, there are still some open questions, that are nicely listed e.g. in an excellent recent review of Chomiuk et al. (2021). Some of these questions are about the nature of the physical processes that make the ejecta spherical or aspherical, the way the mass is ejected in nova eruptions, especially very early, the location of the dust produced in nova ejecta, or the kinematics of the dust.

The only way to address such questions is the use of near-infrared interferometry (Chesneau & Banerjee, 2012).

2. Recent interferometric observations of novae

Interferometric observations do not provide an image of an object; instead, the parameters of the interferometric fringes can be analyzed and modeled. They are a measure of the sizes and shapes of the observed celestial bodies. An additional spectroscopic signal, delivered with the interferogram, allows us to create synthetic three-dimensional data cubes with images of astronomical objects together with corresponding spectra. This is a great advantage of interferometry over other methods of observation, and thus it is sometimes possible to spatially locate regions of emission of specific spectral lines. Another benefit is the unprecedented and unique spatial resolution of milliarcseconds. For a review of the method, see, e.g. Monnier (2003) or Eisenhauer et al. (2023). The past decades have been a time of beautiful development of optical interferometry. There is already a number of published works showing results of this method applied to novae, among them the famous Nova Delphini 2013 (Schaefer et al., 2014). When it comes to the objects of our interest, the previous eruption of RS Oph has been observed with the use of interferometry, with first-generation instruments. Barry et al. (2008) showed already on day 3.8 that the size of the expanding matter was $4.0 - 6.2$ mas in the N-band continuum of the Keck Interferometer Nuller. On day 5.5 the size of $\sim 3 - 6$ mas, depending on the continuum or emission lines chosen in the K-band of VLTI/AMBER, was reported by Chesneau et al. (2007). In turn Lane et al. (2007) used PTI in the K-band and found the size of RS Oph's ejecta to be ~ 3 mas on days $4 - 11$, ~ 6 mas on days $14 - 29$, and $\sim 2 - 3$ mas on days $49 - 121$. Monnier et al. (2006) reported ~ 3 mas for up to 3 months since the eruption in the H-band and K-band of IOTA, Keck, and PTI. Thus, the size estimates of RS Oph after the 2006 eruption were inconclusive.

Recently, there have been new attempts to resolve novae with the use of state-of-the-art interferometers, among them the second-generation instruments of the Very Large Telescope Interferometer (VLTI)[1]. This was possible because V3890 Sgr and RS Oph erupted lately and thus, such observations were acquired and are now being analyzed. For both objects, we performed parametric model fitting with the use of the PMOIRED tool (Mérand, 2022). An example fit is shown in Fig. 1.

V3890 Sgr was observed with the Gravity instrument at VLTI (R=4000, K-band). The broad emission HeI (2.0587μm) line was detected, with a complex shape and several bumps over several thousands of km/s. This target was only marginally resolved, only in the line. The differential phases were characterized by an S-shaped signal and the closure phases were noisy. Nevertheless, it was

[1] https://www.eso.org/sci/facilities/paranal/telescopes/vlti.html

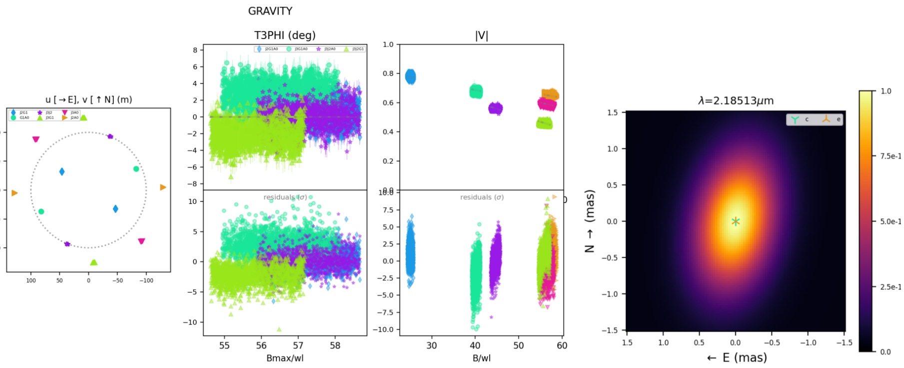

Figure 1. An example simple model of the continuum for RS Oph on day 5 after the last eruption, based on VLTI/Gravity data, performed with the use of the PMOIRED tool. Left: the *u*-*v* covarage representing the configuration of the telescopes used; Center: the closure phase (T3PHI) and visibility (V) signals with models (upper) and residuals (lower panel); Right: the resulting synthetic image of the continuum emission region, modeled as an elongated Gaussian profile. The model represents the size of the source properly (see visibility), whereas does not explain the small closure phase shifts. This means that the continuum-emitting region is clearly elongated but it is in fact more asymmetric than this simple model shows. The following complete modeling of the VLTI data show bipolar ejected matter perpendicular to this continuum signal (Otulakowska-Hypka et al., in preparation).

possible to create a model of the system in this resolved spectral range, showing a bipolar structure.

Next, for RS Oph all the available interferometric instruments were used to monitor the system at several epochs. The amount of data collected in this case was substantial: diverse spectral bands and spectral resolutions, different structures detected in specific lines, plus the overall evolution in time. A detailed description of this analysis is far beyond the scope of this paper and will be published separately (Otulakowska-Hypka et al., in preparation). However, the main findings of this part are that the entire structure of the ejected matter was exceptionally clumpy, also bipolar, and evolved very quickly.

In particular, we modeled the emission lines regions in the spectrum using a number of components of the Gaussian profile. The derived models allowed us to draw conclusions about the sizes and shapes of emitting regions. In addition, observations at different time epochs allowed us to measure the expansion rate of the nova shell and thus calculate the distance to the object (see also Kaczmarek et al. in these proceedings). In both the studied SyRN, apart from the central structure, we found two components located far from the center: blue- and redshifted, representing the bipolar outflows from the systems, confirming the theory of the bipolar model of the ejected material in novae, already at very early epochs.

3. Near future of T CrB

T CrB is the second oldest known RN, with its first observed eruption in 1866 and the last one in 1946. The recurrence time of this star is $\sim$ 80 years, and thus we are now waiting for the next, very rare, once-in-a-lifetime opportunity to observe its eruption.

The visual brightening of T CrB rise from V=10 mag to V=2 mag as it is located at only $\sim$ 900 pc. This proximity gives an opportunity to study spatial structure in unprecedented detail. There is no better source with more optimal parameters for our scientific goal and from the point of view of the available interferometers.

There are observational indications that this next outburst is about to occur soon. Namely, a brightening in the optical bands that lasted from 2014 until recently and a pre-eruption dip. Similar photometric behavior was present before the 1946 outburst (Schaefer, 2023). Like most of the world-wide astronomical community, we look forward to the coming T CrB outburst and plan to monitor it closely with optical interferometers: before, during, and after the eruption. Among other things, we are, of course, interested in the morphology and kinematics of the event and its evolution. In addition, we will monitor the secondary eruption of T CrB, any signs of renewed accretion during the first weeks after eruption, to determine its influence on mass transfer to the WD. The best we can hope for is to resolve the stellar components. It is only possible for such a nearby nova, and only now – with the use of the second-generation instruments at VLTI and CHARA[2].

4. Conclusions

V3890 Sgr and RS Oph have recently erupted and T CrB is expected to erupt soon. This makes the current times a wonderful epoch to study these systems, given their rarity and recurrence times.

With the data of the two SyRN that are ready, and when T CrB erupts, we investigate the morphology and kinematics of the novae ejecta, as well as their asymmetry and very complex geometry, which are seen in emission lines and in the continuum. Such modeling of interferometric data is difficult and requires novel approaches, especially in the case of complex novae systems.

Optical interferometry gives us unprecedented angular resolution that is needed for comparison with existing detailed 3-D numerical simulations (e.g. Booth et al. (2016)), and to address the open questions in the theory of novae.

[2]the Center for High Angular Resolution Astronomy, https://www.chara.gsu.edu

Understanding eruptions of RN is important not only for cataclysmic variable stars. It also applies to the subjects of shock propagation (as compared to those in supernovae), as well as search of Type Ia supernovae progenitors. RN are one of the most promising objects in this context, since their white dwarfs are very massive, close to the Chandrasekhar limit, and the mass accretion rate is high.

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[3] https://ncn.gov.pl
[4] https://idub.amu.edu.pl/

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