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Probing the accretion process onto the white dwarf
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ARAS observing proposal:
Probing the accretion process onto the white dwarf in the recurrent symbiotic nova RS Oph between its nova explosions

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Symbiotic stars are the widest interacting binaries, whose orbital periods run from hundreds of days (S-type systems containing a normal giant) to decades or even to hundreds of years (D-type systems containing a Mira variable surrounded by a dust shell). The evolved red giant (the cool component) is the donor star and a hot compact star, mostly a white dwarf (WD, the hot component), accretes from the giant's wind. Accretion process generates a very hot ($T_h > 10^5$ K) and luminous (L_h ~ 10 – 10^4 solar units) source of radiation, which ionizes a fraction of the neutral giant's wind giving rise to nebular emission. This configuration represents the so-called quiescent phase, during which the processes of the mass-loss, accretion and ionization are in a mutual equilibrium, and thus the symbiotic system releases its energy approximately at a constant rate and temperature.

Main energy sources

During quiescent phase, the accreting WD can generate its luminosity by two different ways:

(i) In most cases, a large amount of energy in order of thousands solar luminosities is believed to be powered by stable nuclear burning of hydrogen on the WD surface (e.g., Z And, BF Cyg, SY Mus, AG Dra). This means that the hydrogen rich material is burnt at the same rate as it is accreted. However, this situation requires a certain range of accretion rates that depends on the WD mass. For example, low-mass WDs (M_{WD} ~ 0 .5 – 0.6 solar masses) need to accrete a few times 10^{-8} up to ~ 10^{-7} solar masses per year, while massive WDs (M_{WD} ~ 1.3 – 1.4 solar masses) need to accrete around of 4 – 5 times 10^{-7} solar masses per year to burn the incoming fuel at the same rate – i.e. to sustain stable hydrogen burning on their surface.

(ii) In rare cases, low luminosities of a few times 10^1 – 10^2 solar units are generated solely by the accretion process onto the WD, when its gravitational potential energy is converted into the radiation by the disk (e.g., EG And, CH Cyg, 4 Dra, SU Lyn). This happens when the accretion rate is below the stable-burning limit. Then the accreting H-rich material cannot nuclearly burn, and thus is gradually accumulated on the WD surface via the accretion disk. Due to the viscosity, the disk material is gradually heated at the expense of its binding energy (kinetic and potential). This leads to its shifting in radial direction to the central accretor by spiraling to regions with smaller and smaller potential energy, and finally decelerating at the WD surface, losing the rest of its kinetic energy in a thin layer, called the boundary layer. In this way, the accretion disk effectively converts the gravitational-potential energy of its material to the radiation. Therefore, maximum luminosity liberated during the accretion process is given by the initial potential energy of the accreting material in the gravitational field of the WD, i.e., $L_{acc} = G\ M_{WD}\ (dM/dt)_{acc}\ /R_{WD}$. Thus, depending on mass and radius of the WD and the accretion rate, $(dM/dt)_{acc}$, we observe a relatively low luminosities with respect to the case (i).

If the accretion rate for some reasons increases above the level sustaining the stable burning (e.g., due to an increase of the mass-transfer from the giant and/or a disk instability), a fraction of the accreting material blows up from the WD in the form of wind. The system brightens up in the optical by a few magnitudes and shows signatures of a mass-outflow. The luminosity can be as high as the Eddington limit. The corresponding brightening is called as `Z And-type' outburst. It evolves on the time-scale of weeks to years, often showing multiple outbursts in the optical light curve. This stage is called as active phase of symbiotic star.

On the nova phenomenon

Considering the case (ii) above, the amount of material accreted onto the WD will increase up to a critical value, M_{crit}, which applies a critical pressure at the base of the accreted envelope, P_{crit} that ignites thermonuclear runaway (TNR) on the surface of WD – we observe the nova phenomenon.

If this happen in a short-period binary with a Roche-lobe filling subdwarf, we talk about classical novae. If the TNR occurs in symbiotic binary, we talk about symbiotic novae (e.g., V1016 Cyg, V1329 Cyg, PU Vul, HM Sge). In the latter case we observe much smaller amplitudes of the brightening ($\Delta m > 3$ mag) than in the former case, because the light from TNR is superposed with the light from the bright red giant.

Depending on the WD mass and the accretion rate we observe either very slow novae, whose outbursts last for dozens of years, or very fast novae lasting for several days to months. After the nova explosion, accretion process re-establishes, new material is accumulating again up to the critical value, at which a new TNR is ignited. From this point of view all novae are recurrent. However, we use the term ‘recurrent novae’ only for those, whose recurrence time is comparable with the human life. Symbiotic stars that show this type of regular outbursts are called as recurrent symbiotic novae (e.g., RS Oph, T CrB). It is quite easy to show that the recurrence time strongly depends on the WD mass. The critical mass is attracted to the WD surface by the gravitational force $F_{grav} = G\ M_{WD}\ M_{crit}/R_{WD}^2$, which for spherical envelope exerts the pressure, $P_{crit} = F_{grav}/4\pi R_{WD}^2 = G\ M_{WD}\ M_{crit}/4\pi R_{WD}^4$.

According to the WD mass-radius relation (e.g., $R_{WD} \sim 0.01\ R_{Sun}$ and a few times 0.001 R_{Sun} for a 0.5 M_{Sun} and 1.3 M_{Sun} WD, respectively), one can recognize that high mass WD can accrete significantly smaller value of M_{crit} (a few times $10^{-6}\ M_{Sun}$) than a low mass WD (M_{crit} can be as high as $\approx 10^{-2}\ M_{Sun}$) to obtain a TNR for given Pcrit of, say, $\approx 10^{20}$ dyne/cm^2. For example, accretion at $\sim 10^{-7}\ M_{Sun}$/year onto a high mass WD will accumulate M_{crit} for decades only, while for a 0.5 M_{Sun} WD this will take in order of 10^5 years. That is why recurrent novae contain high mass WDs, near the Chandrasekhar limit, and thus represent promising progenitors of Supernova Ia explosions.

Recurrent symbiotic nova RS Oph – accreting to explode in 2026

One of the famous recurrent symbiotic novae is the star RS Ophiuchi (RS Oph). The binary consists of a late-type K7 III giant and a WD with a mass close to the Chandrasekhar limit, in a 454-day orbit. Its nova-like outbursts are characterized with brightening by about 7 mag and a recurrence period of about 20 years. Historically, 6 eruptions have been recorded unambiguously. The first one in 1898, the last one on February 12.83, 2006 and the next one is thus expected during 2026-27. So, currently RS Oph occurs at the stage of intense accretion of material onto the WD from the wind of its red giant companion. The short recurrence time and a bright peak magnitude, V = 4-5, make RS Oph a good target for multifrequency observational campaigns. Figure 1 shows light curves of RS Oph from its last 2006 outburst to 2018.6.

During the quiescence, i.e., between the nova outbursts, the flat UV/optical continuum satisfies radiation produced by a large optically thick accretion disk ($R_{disk} > 10\ R_{Sun}$). Example of the spectral energy distribution (SED) model from far-UV to near-IR on day 614 after the maximum of the 2006 outburst is shown in Fig. 2.

The luminosity of the disk, ≈ 400/cos(i) L_{Sun} , corresponds to an accretion rate of ~2.4 x 10^{-7} M_{Sun} / year for M_{WD} = 1.3 M_{Sun} , R_{WD} = 0.004 R_{Sun} , i = 50 degrees and considering that one quarter of the total gravitatioinal-potential energy of WD is converted into radiation. verted into radiation. This implies that the high mass WD in RS Oph is accreting just below the stable burning limit. During the 20 years of quiescence, the WD thus accumulates the mass of ~4.8 x10^{-6} M_{Sun}, which is sufficient to ignite a new explosion that is expected during 2026. The presence of a disk-like formation around the WD during the out-of-outburst stage of RS Oph is also supported by a significant 0.4 mag rapid light variation on the time scale of decades of minutes (see Fig. 3). Another interesting feature of the RS Oph spectrum between outbursts, which reflects a strong accretion process, are markedly variable broad Hα emission wings. Figure 4 shows example of the bottom part of the Hα line profiles with the satellite emission components. They can reflect a high-velocity bipolar outflows from the accreting WD. Probably a result of transient abrupt accretion from the disk.

Proposal for spectroscopic observations

To understand better the connection between the disk and the mass accretion/ ejection onto/from the high-mass WD in RS Oph during its `quiet' stage before the expected 2026 nova explosion, we suggest to carry out spectroscopic observations for the following reasons:

1. Medium resolution spectra with R > 9000 will be used for:
(i) measuring abrupt changes in the profiles of Hα and Hβ lines.
(ii) to support the presence of a cool shell around the WD by radial velocities of absorption lines of neutral metals. They should be placed at the anti-phase to those from the red giant.
(iii) to estimate the mass-loss rate via the irregular clumpy mass ejections by means of the Hα method.
(iv) to identify the source of the rapid variability indicated in the continuum by the flickering fluctuations on the time-scale of minutes to hours.

2. Low-resolution spectra with R = 500-1000 covering the largest wavelength range as possible will be used to model the SED. On the basis of disentangling the composite optical continuum we will reconstruct the structure of the WD pseudophotosphere.

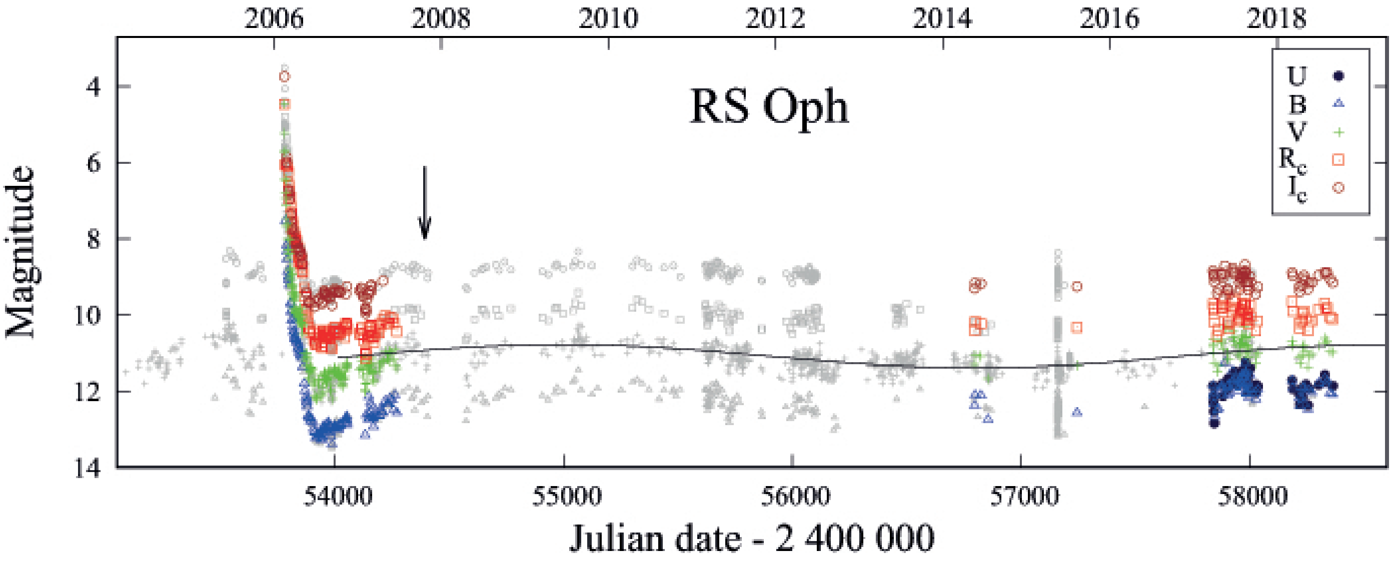

Figure 1. Light curves of RS Oph from ~2004 to 2018.6, containing the last outburst peaked on February 12.83, 2006. Gray points represent data from the AAVSO database. The arrow marks date of the SED model shown in Fig. 2. The solid line represents a sine function with amplitude ΔV ~ 0.3 mag and a period of ~9.4 years (according to Sekeráš et al. 2019, CoSka, 49, 19-66).

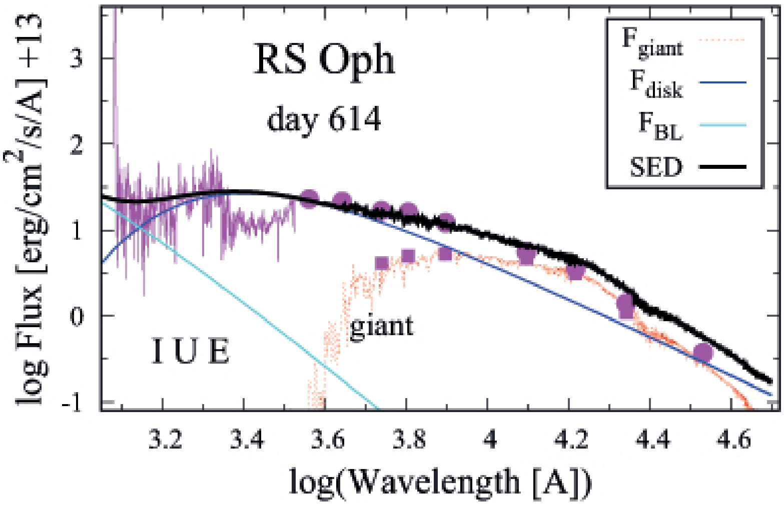

Figure 2. The SED model (black line) during the post-outburst phase of RS Oph (at the nova age of 614 days after the 2006 maximum, marked by arrow in Fig. 1). The observed SED is determined by the IUE spectrum and photometric flux-points (in magenta). The model is given by superposition of radiation from accretion disk (blue line), boundary layer (cyan) and the giant (dotted red line). Adapted according to Skopal, 2015, NewA, 34, 123-133.

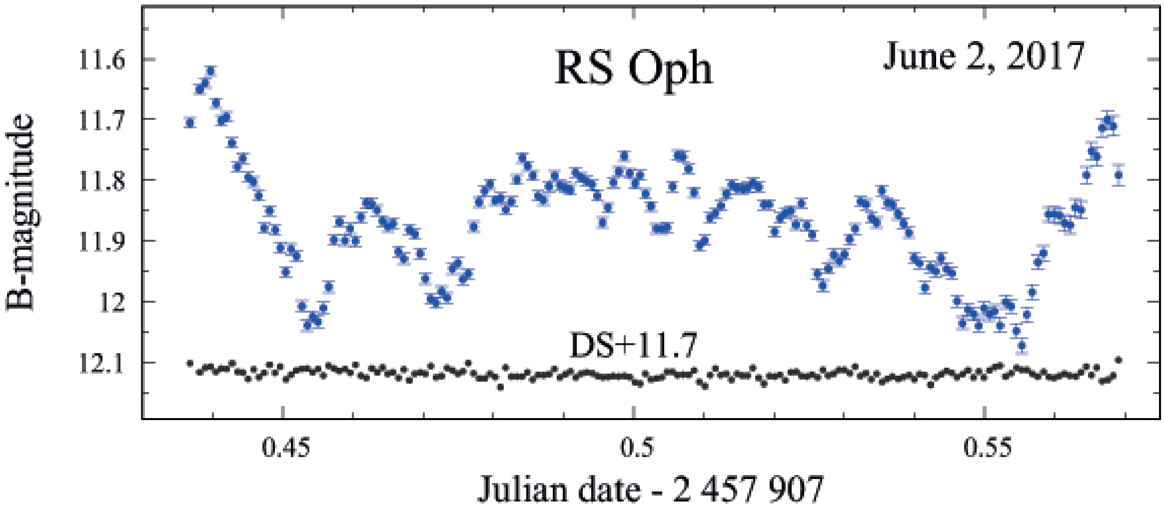

Figure 3. Example of rapid photometric variability of RS Oph in B band (blue points). The stars HD162215 and UCAC4-416-072918 were used as comparison and check star (ΔS is their difference). Adapted according to Sekeráš et al. 2019, CoSka, 49, 19-66).

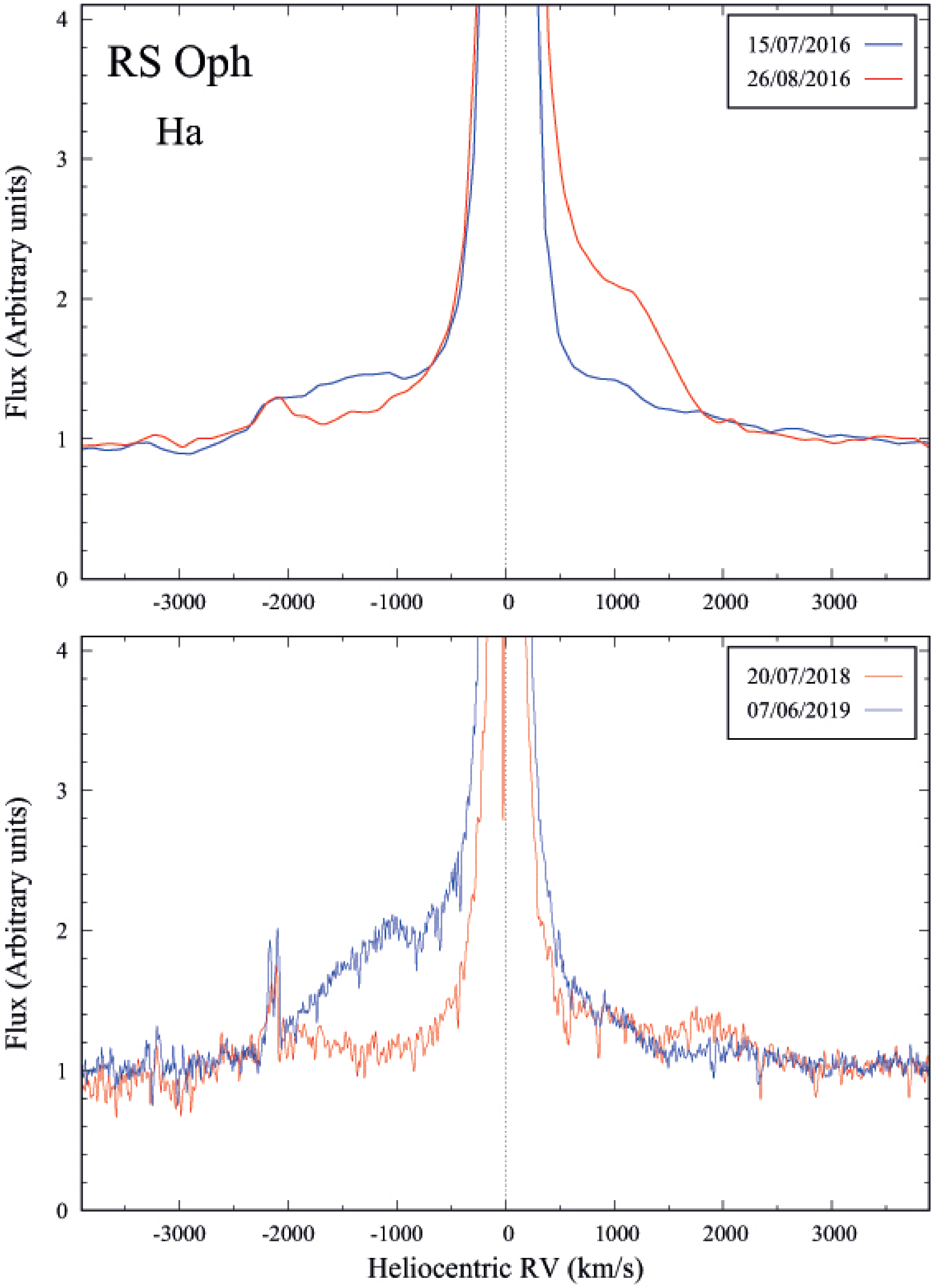

Figure 4. Strong variability in the broad wings of the Hα line. Top: low-resolution spectra (R~1037) carried out by J. Guarro. Bottom: middle-resolution spectra (R~12000 – 14000) taken by T. Lester.