Hα spectroscopy of the recurrent nova RS Oph during the 2021 outburst

R. K. Zamanov¹, K. A. Stoyanov¹, Y. M. Nikolov¹, T. Bonev¹, D. Marchev², S. Y. Stefanov¹,³

¹ Institute of Astronomy and National Astronomical Observatory, Bulgarian Academy of Sciences, Tsarigradsko Shose 72, BG-1784, Sofia, Bulgaria
² Department of Physics and Astronomy, Shumen University "Episkop Konstantin Preslavski", 115 Universitetska Str., 9700 Shumen, Bulgaria
³ Department of Astronomy, Sofia University "St. Kliment Ohridski", James Bourchier 5, BG-1164 Sofia, Bulgaria

rkz@astro.bas.bg kstoyanov@astro.bas.bg

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Here we present Hα observations of RS Oph from 2021 Aug 16 to 2021 Aug 23 and discuss (1) the P Cyg type profile at the top of the emission and (2) the absolute magnitude of the red giant.

1 Observations

High-resolution optical spectra of RS Oph are secured with the Coudè spectrograph attached to the 2m telescope of the Rozhen National Astronomical Observatory, located in Rhodope mountains, Bulgaria. The spectra cover 225 Å around the Hα line with a resolution of 0.11 Å/pixel. The spectra are reduced in the standard way including bias removal, flat-field correction, and wavelength calibration using the routines provided in IRAF (Tody 1993). The wavelength calibration is done with Thorium-Argon (Th-Ar) hollow cathode lamp and tuned using the telluric lines imprinted in the spectrum (see Fig. 3 in Appendix). The FWHM (full width at half maximum) of the Th-Ar lines is 0.4 Å, the FWHM of the telluric lines is 0.5 Å. The spectra cover the wavelength range from 6450 Å to 6675 Å. The spectra are available upon request from the authors and on Zenodo (zenodo.org/record/5524465).

For comparative purposes, we also use two spectra obtained with the Echelle spectrograph of the same telescope in 2019 and 2020, and one spectrum obtained with an 11 inches Celestron C11 telescope and L hires III spectrograph. Two observations of the Hα emission line are plotted on Fig. 1. One of them is before the outburst (5 September 2020) and the second is in outburst (21 August 2021). In outburst, the Hα emission is of about 20 times stronger and 5 times wider.

The journal of observations and the measured parameters of Hα line are given in Table 1:

- column 1 - date of observation (in format YYYY MM DD HH:MM). The time is the start of the exposure.
- column 2 - telescope and spectrograph;
- column 3 - the exposure time in minutes;
- column 4 - the total equivalent width of Hα emission line;
- column 5 - the FWHM of the Hα emission line. This is the FWHM of the strong broad component only. This component is emitted from the expanding envelope.
- column 6 - the wavelength of the diffuse interstellar band DIB 6613, which is used for check of the wavelength calibration;
- column 7 - the heliocentric radial velocity of the absorption part of the P Cyg profile. For the spectra 20190718 and 20200905, column 7 is the heliocentric radial velocity of the central dip, located in between the blue and red peaks.
- column 8 - the heliocentric radial velocity of the emission part of the P Cyg profile.

2 Results

In our data set is visible that (1) the FWHM of the the strong Hα emission originating from the nova ejecta is monotonically decreasing from 45.8 Å on
Table 1. Journal of observations and some parameters of Hα line. In the columns are given as follows: date of observation (in format YYYY MM DD HH:MM), telescope and spectrograph, exposure time in minutes, the equivalent width of Hα emission line, FWHM of the broad component of the Hα emission line, the heliocentric wavelength of the DIB 6613, radial velocity of the absorption and emission components of the P Cyg emission.

| Date-obs | telescope | expo | EW Hα | FWHM Hα | DIB6613 | RV_{abs} | RV_{em} |
|----------|-----------|------|-------|----------|---------|----------|---------|
| 2019 07 18 20:06 | 2m Ech | 60 | | | 6613.369 | -70.6 ± 1.5 |
| 2020 09 05 19:07 | 2m Ech | 30 | | | 6613.318 | -62.3 ± 1.5 |
| 2021 08 12 20:32 | C11” | 30 | -780±80 | 45.8 ± 0.5 | 6613.305 | -69.7 ± 2.0 | -9.1 ± 2.0 |
| 2021 08 16 20:28 | 2m Coude | 3 | -1350±60 | 35.7 ± 0.3 | 6613.337 | -71.2 ± 2.0 | -11.6 ± 2.0 |
| 2021 08 17 20:25 | 2m Coude | 5 | -1300 : | 33.2 ± 0.4 | 6613.321 | -73.2 ± 2.0 | -12.3 ± 2.0 |
| 2021 08 19 20:01 | 2m Coude | 5 | -1650±60 | 30.0 ± 0.3 | 6613.321 | -72.9 ± 2.0 | -7.3 ± 2.0 |
| 2021 08 20 19:17 | 2m Coude | 5 | -1770±70 | 28.6 ± 0.3 | 6613.391 | -72.9 ± 2.0 | -7.3 ± 2.0 |
| 2021 08 22 19:01 | 2m Ech | 10 | -1940±50 | 27.7 ± 0.3 | 6613.342 | -74.2 ± 2.0 | -9.2 ± 2.0 |
| 2021 08 23 19:46 | 2m Ech | 5 | -1910±95 | 26.3 ± 0.3 | 6613.353 | -74.2 ± 2.0 | -9.3 ± 2.0 |

12 August 2021 to 24.5 Å on 23 August 2021 (see Table 1, column 5); and (2) its EW is increasing. A more detailed atlas can be found in Munari & Valisa (2021b).

2.1 Absolute V magnitude (M_V) of the mass donor

The light curves of RS Oph during the last 30 years are well documented in AAVSO data. In quiescence the V band magnitude of RS Oph is 10.2 < m_v < 11.3. According to the AAVSO V-band light curve, the maximum brightness of RS Oph during the outburst is V=4.593 mag. The observations suggest an outburst amplitude of ∼ 6 – 6.5 mag. To calculate the absolute V band magnitude we use the well known formula:

\[ M_V = m_V - 3.1E_{B-V} + 5 \log_{10}(d/10), \]

where m_V is the apparent V band magnitude, E_{B-V} is the interstellar reddening, d is the distance in parsecs. For RS Oph E_{B-V} = 0.69 ± 0.07 (Zamanov et al. 2018), and d = 2600 pc (GAIA eDR3, Gaia Collaboration et al. 2021). Using V=4.593 mag, we obtain an absolute V magnitude at the maximum M_V ≈ −9.69 mag.

The brightness of the red giant in RS Oph is m_V ≈ 12.26 (Zamanov et al. 2018). Using again Eq. 1, we obtain that the absolute V-band magnitude of the red giant is M_V ≈ −2.02 mag. Following Straizys & Kuriliene (1981) M2III giant has absolute V magnitude M_V = −0.9, while for luminosity class II, M2II – M_V = −3.0. It means that the new GAIA distance puts the red giant of RS Oph in between luminosity classes III and II. It is worth noting that with the old value d = 1600 pc (Bode 1987), the red giant would have M_V ≈ −1.0, in agreement with M2III spectral type.
Fig. 1. A comparison between the Hα line profiles at quiescence (2020 Sep 5) and in outburst (2021 Aug 21). In outburst, the Hα emission is $\sim 20$ times stronger and $\sim 5$ times wider.

Fig. 2. (a) Hα profiles observed on 12 August 2021 and 16 August 2021. A sharp P Cyg (emission + absorption) component is visible at the top of the strong emission. (b) Expanded view of the P Cyg profile. The average positions of the emission ($-9$ km s$^{-1}$), and the absorption ($-74$ km s$^{-1}$) are marked with arrows. The systemic velocity ($-39$ km s$^{-1}$) is marked with vertical green line.
2.2 P Cyg profile

On Fig. 2a are plotted the Hα profiles observed on 12 August 2021 and 16 August 2021. A sharp P Cyg component is visible at the top of the strong emission. It is superimposed on the broad emission line. It probably is due to the outer parts of the slow wind of the red giant and/or the material from the previous outbursts ionized by the nova outburst. It consists of an blue absorption and red emission. It is strong and very well visible on the low resolution spectrum obtained on 12 August 2021. We measure the heliocentric radial velocity of these P Cyg absorption and emission. They are given in Table 1. The average position of the P Cyg absorption is $RV_{abs} = -74 \pm 2$ km s$^{-1}$ and of the P Cyg emission is $RV_{em} = -9 \pm 3$ km s$^{-1}$. The position of the absorption is close to the radial velocity of the central dip of Hα at quiescence.

The analysis of the CaII and NaD lines of RS Oph (Patat et al. 2011) reveals at least three distinct circumstellar components at $-77$ km s$^{-1}$, $-63$ km s$^{-1}$, and $-46$ km s$^{-1}$, respectively. Our measurements indicate that probably, the component at $-77$ km s$^{-1}$ is visible in our Hα spectra.

On Fig. 2b is plotted an expanded view of the P Cyg profile. The average positions of the emission ($-9$ km s$^{-1}$), and the absorption ($-74$ km s$^{-1}$) are marked with red and blue arrow, respectively. The systemic velocity of RS Oph is estimated $\gamma = -38.7 \pm 0.4$ km s$^{-1}$ (Brandi et al. 2009) and $\gamma = -40.22 \pm 0.64$ km s$^{-1}$ (Fekel et al. 2000). The systemic velocity is marked with vertical green line.

Using the velocities given in Table 1, we can estimated the outflowing velocity, $V_{out}$, as $V_{out} = RV_{em} - RV_{abs} = 64 \pm 4$ km s$^{-1}$ and $V_{out} = \gamma - RV_{abs} = 34 \pm 2$ km s$^{-1}$. These two values should be considered as limits, and consequutively our estimate of the outflowing velocity of the material surrounding RS Oph is $32$ km s$^{-1} \leq V_{out} \leq 68$ km s$^{-1}$ (1σ error is taken into account).

Such velocities have been observed from the circumstellar envelopes of a few supernovae – SN 1991T, SN 1998es, SN 2006X (see Fig. 1 of Patat 2013). This similarity is a clue that the progenitor systems of some Type Ia supernovae can be former recurrent nova systems like RS Oph (e.g. Patat et al. 2011).

Conclusions: We report spectroscopic observations of the recurrent nova RS Oph obtained before and during the 2021 nova outburst. For the material surrounding RS Oph, we find outflowing velocity $32$ km s$^{-1} \leq V_{out} \leq 68$ km s$^{-1}$, which is similar to the circumstellar envelopes of some supernovae. We note that the new GAIA distance indicates that the red giant should be probably classified in between II and III luminosity class.

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3 Appendix: Telluric lines around $H\alpha$

The following telluric lines: 6532.359, 6543.907, 6548.622, 6552.629, 6557.171, 6572.072, 6574.847, 6580.786, 6586.596, 6599.324 are marked on Fig. 3. They are used for tuning the wavelength calibration.

Fig. 3. Telluric lines imprinted onto the $H\alpha$ emission of RS Oph.