RS Ophiuchii: Rapid early evolution of the 2021 explosion

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1. Accreting WDs – the essence of their recurring explosions
2. The case of the symbiotic binary RS Oph – an introduction
3. SED models – parameters & bipolar structure of the ejecta
4. Broad & narrow components of emission lines
   (penetration of the ejecta into the relatively stable wind from the giant)
4. Gamma-rays & shock powered outburst

T.L., December 3, 2025

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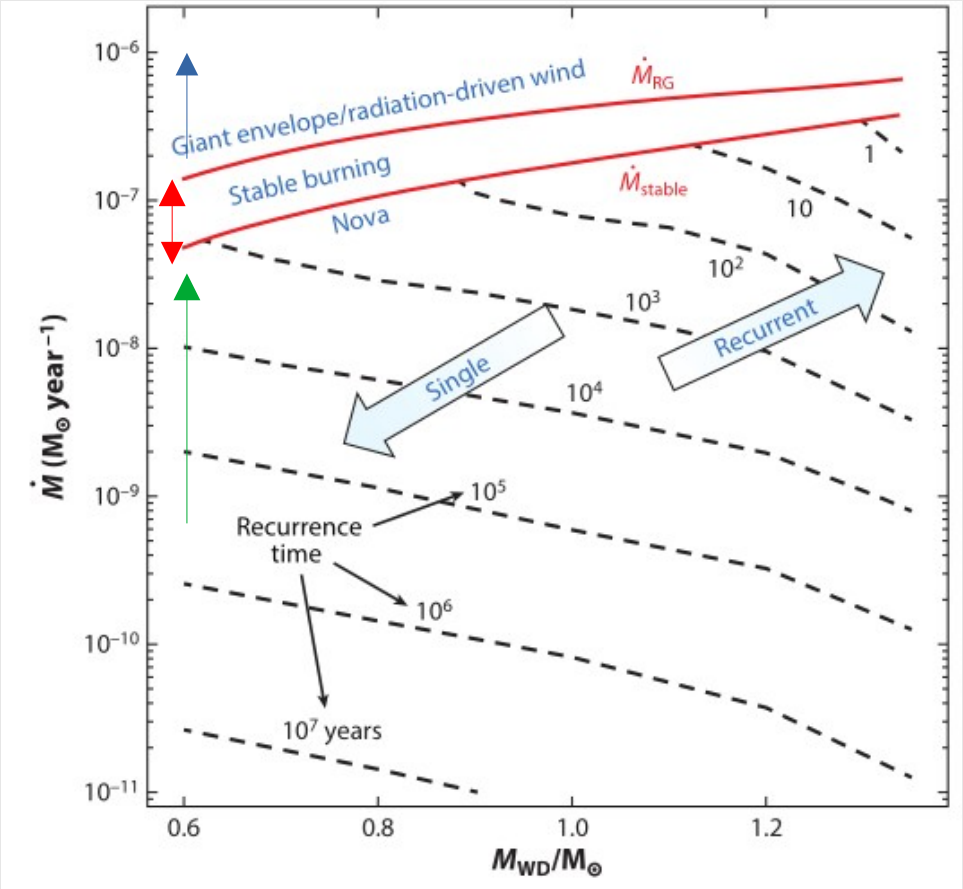
Accreting white dwarfs with recurring explosions



- - - constant recurrence time

Adapted from Chomiuk et al. (2021)

Accreting WD increases its mass:

(i) at low rates up to $\Delta M \rightarrow P_{crit}$: ignition of a nova outburst.

High M_{WD} & M_{acc}

→

short recurrence time

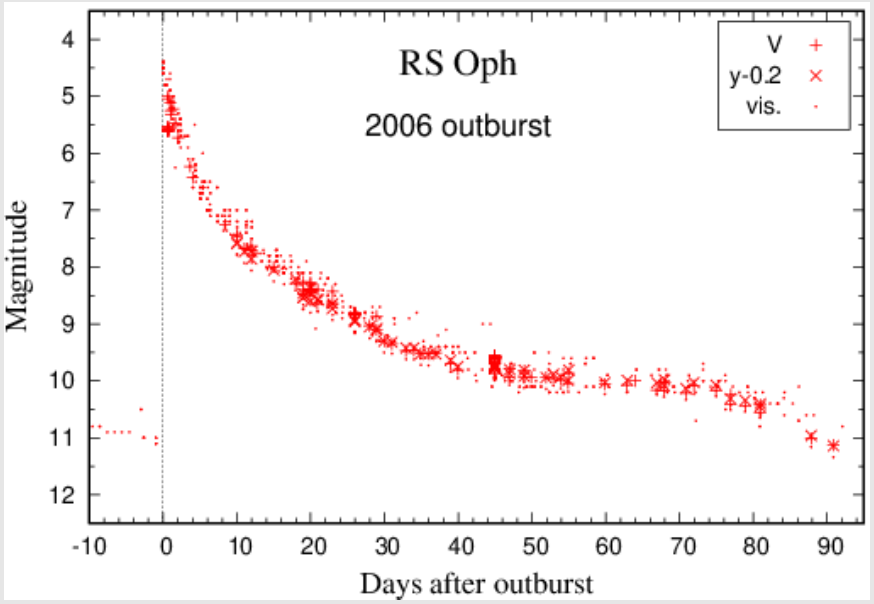
(ii) at high rates of ~10^{-7} M_{Sun}/year: stable H-burning in a shell

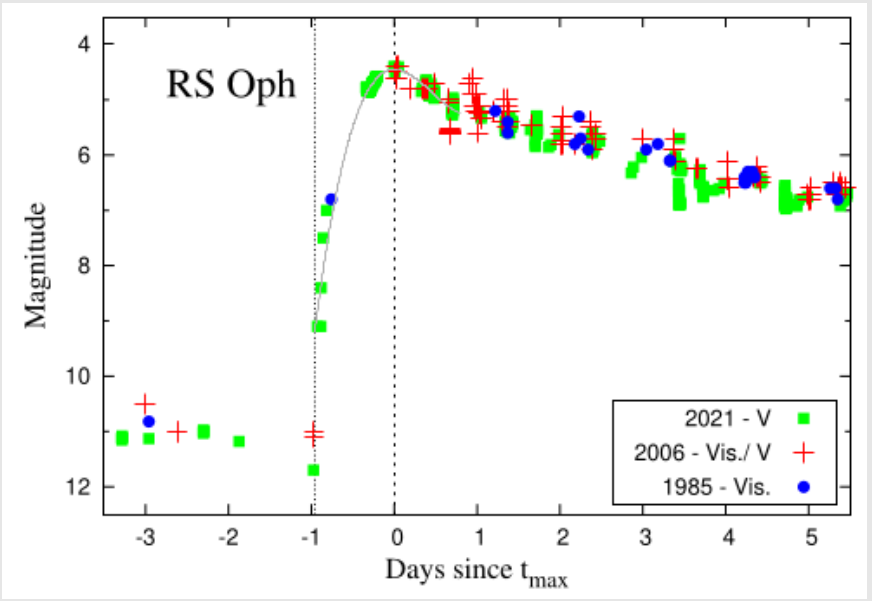
(iii) if rates >~10^{-7} M_{Sun} /year: Z And-type outbursts

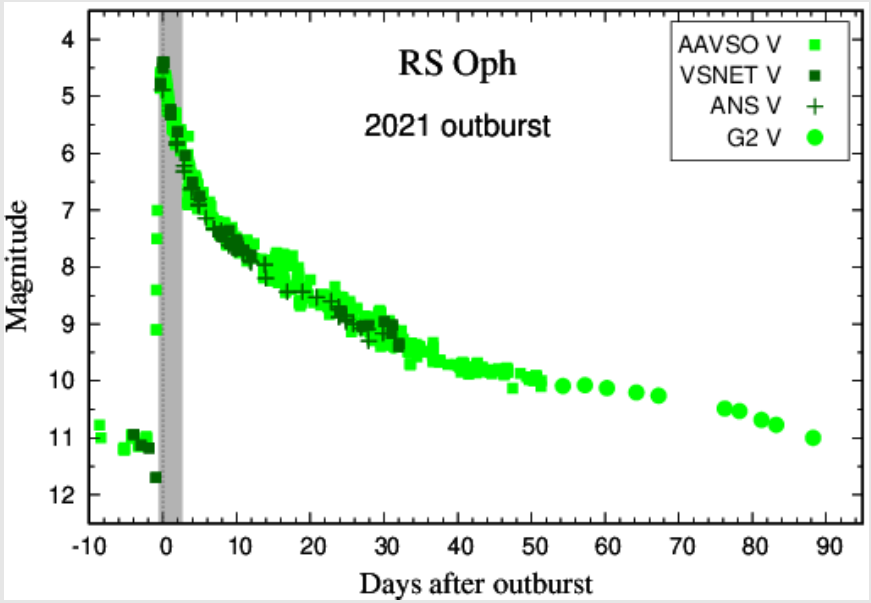
(e.g., Paczynski & Zytkow 1978, ApJ, 222, 604; Yaron, et al., 2005, ApJ, 623, 398; Hachisu et al., 1996, ApJ, 470:L97; Skopal et al. 2017, A&A, 604, A48)

The recurrent symbiotic nova RS Oph

K-giant + WD (M_{WD} ~ 1.3 Mo), P_{orb} = 455 d, P_{rec} ~ 15-20 years







The striking similarity of RS Oph outbursts allows us to consider observations obtained on the same day after the outburst as (near-)simultaneous – an important assumption for multivawelength SED modeling.

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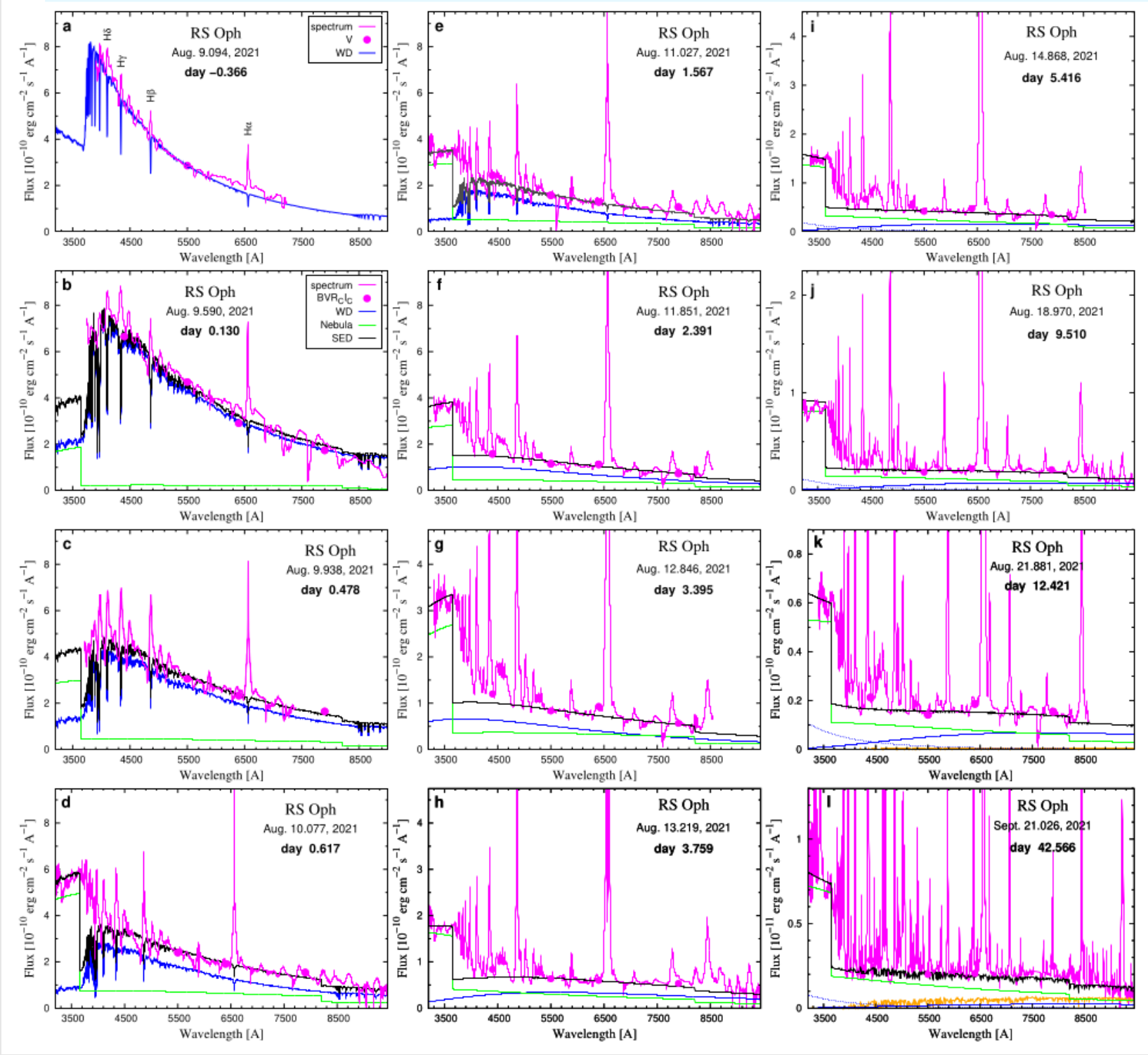
Evolution of the spectral energy distribution (SED) in the optical spectrum



Examples of SEDs of RS Oph from the onset of its 2021 explosion: From day - 0.37 to day + 42.6

Spectrum

BVR_CI_C

WD

Nebula

SED

Two-temperature type of the spectrum:

$$L_H(shell) \ll \alpha_B(H, T_e) \times EM$$

→

Non-spherical pseudophotosphere

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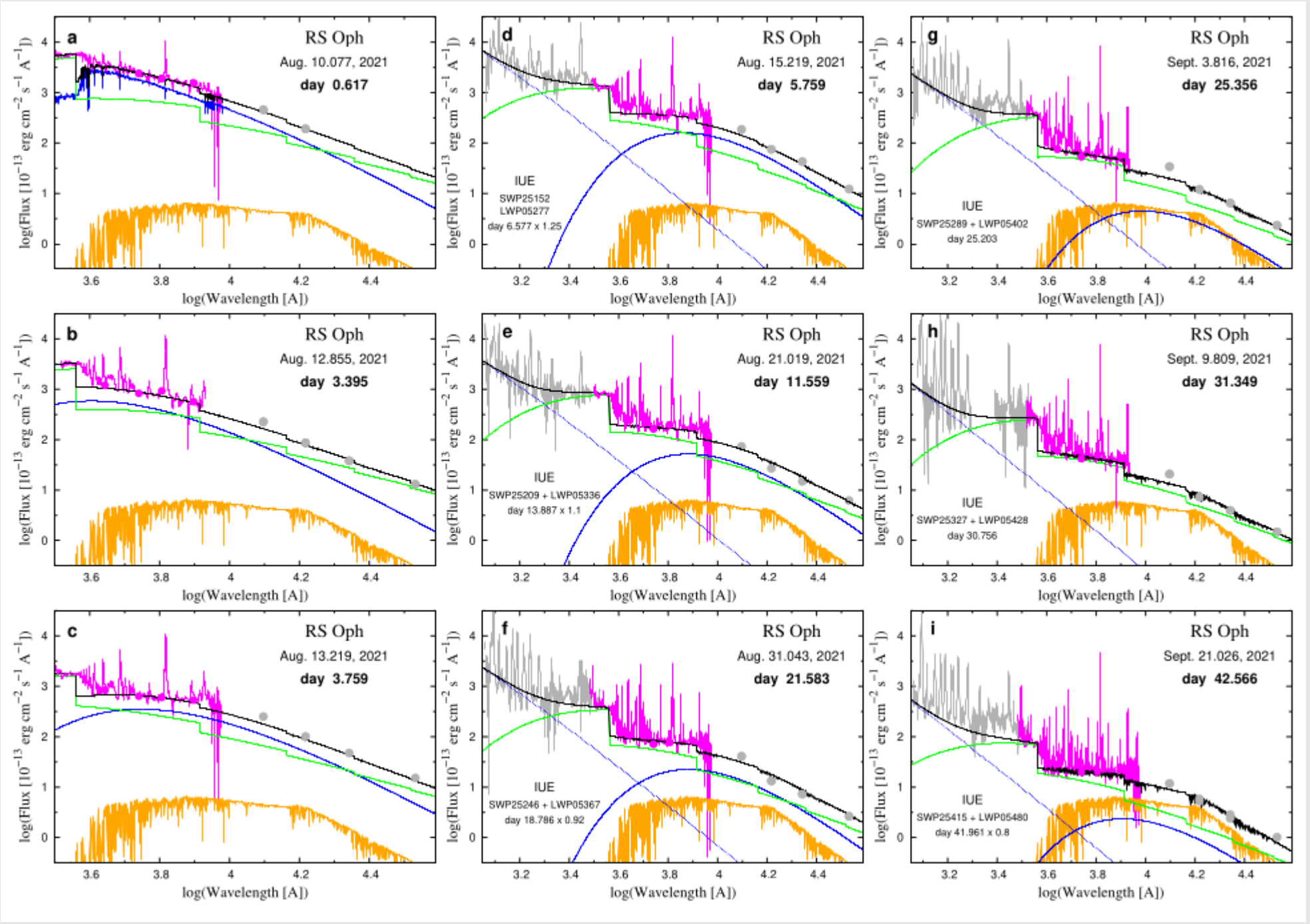
Evolution of the SED in the ultraviolet / optical / near-IR spectrum



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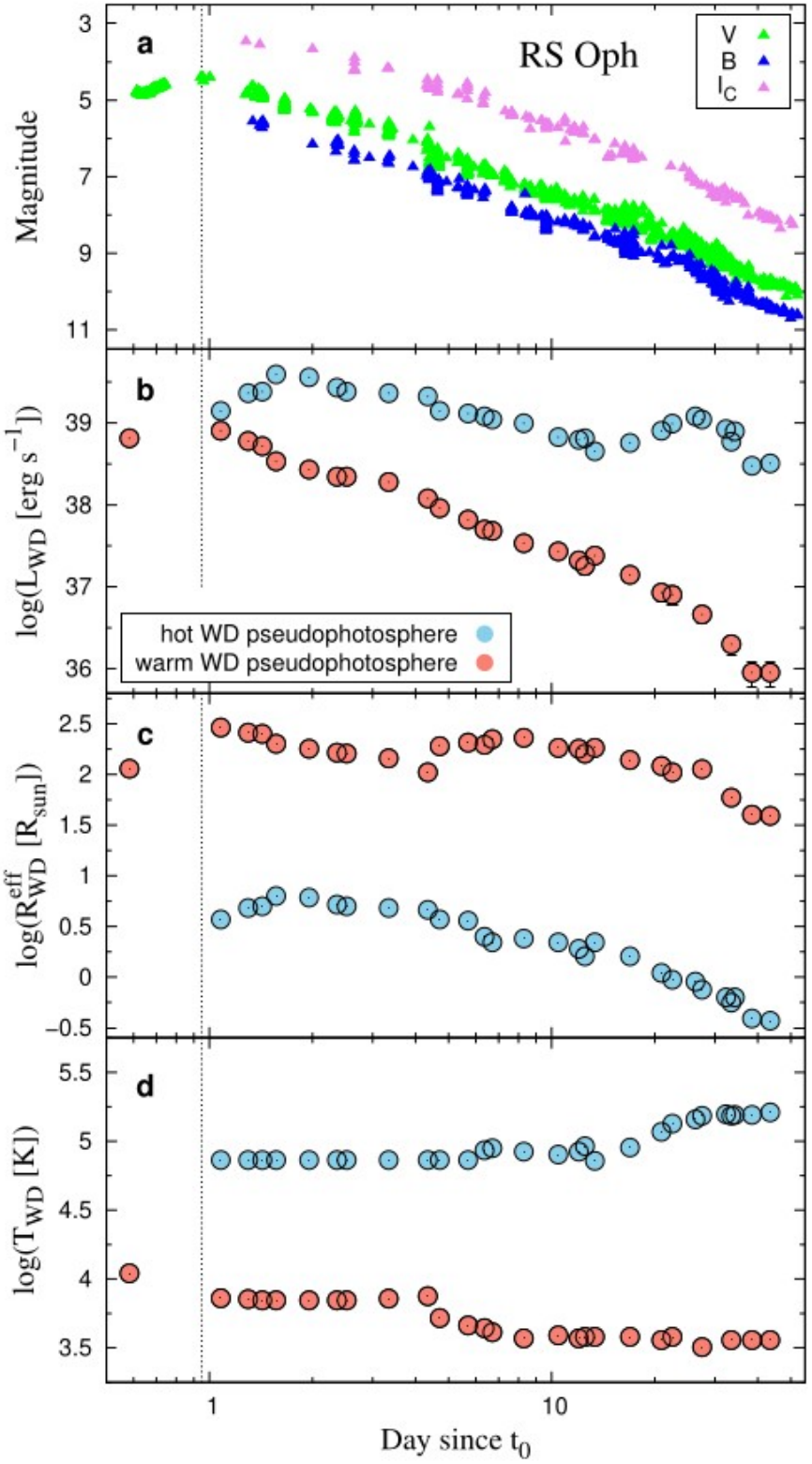

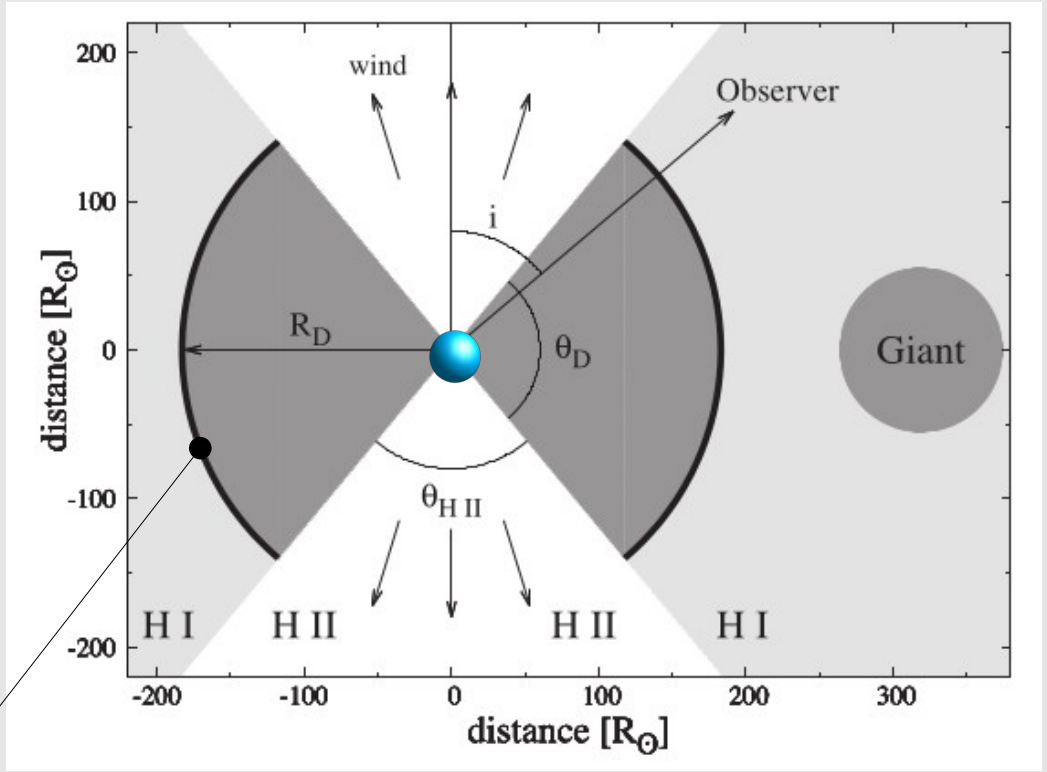

- warm WD pseudophotosphere

$$F(\lambda) = \theta^2_{WD}\,\pi\,B_\lambda(T_{eff\,/BB}) + k_N \times \epsilon(\lambda, T_e)$$

$$R^{eff}_{WD} = \theta_{WD} \times d\,,\quad L_{WD} = 4\pi d^2 \theta^2_{WD} T^4_{eff}$$

$$L_{ph}(\text{shell}) \ll \alpha_B \times EM \text{ - biconical structure}$$

- hot WD pseudophotosphere

$$L_{ph} = \alpha_B(H^0, T_e)\,EM$$

$$L_{WD} = \alpha_B(H^0, T_e)\,EM\,\frac{\sigma T^4_{BB}}{f(T_{BB})},\quad f(T_{BB})[cm^{-2}s^{-1}]$$

T_{BB} - by indirect methods

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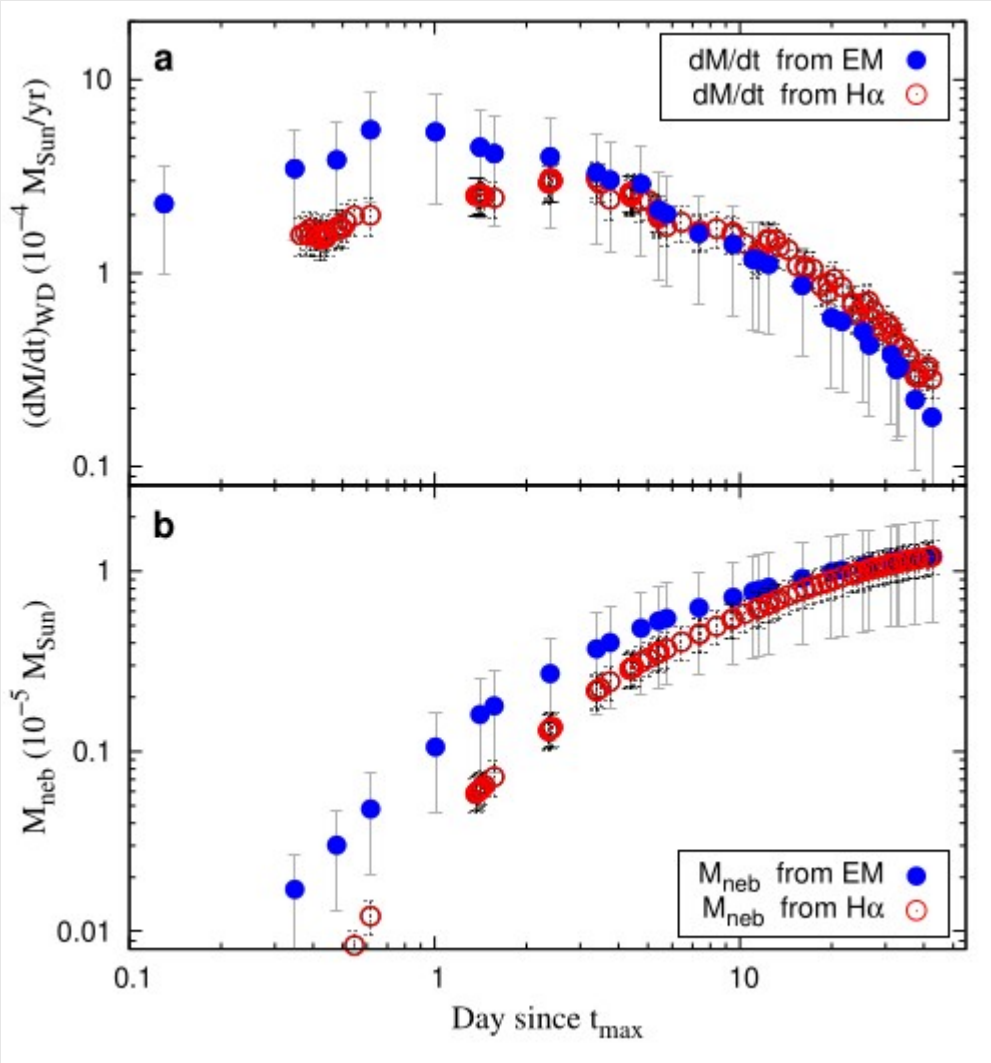
Evolution of the mass-loss rate and the ejected mass



a Mass-loss rate by the ionized part of the ejecta.

b Corresponding mass, M_{neb} .

- The mass-loss rate of the ionized ejecta:

$$EM \propto \left(\frac{\dot{M}_{WD}}{v_\infty}\right)^2$$

$\mathrm{EM} \sim (4.9 - 0.11) \times 10^{62}$ cm^{-3}

$v_\infty \sim 4000 - 4500$ km/s

$\dot{M} \sim (5.5 - 0.2) \times 10^{-4}$ M_{Sun} yr^{-1}

From the Hα flux, Fα :

$$4\pi d^2 F_\alpha = h\nu(H_\alpha)\,\alpha(H_\alpha, T_e) \times EM$$

$h\nu(H\alpha)\alpha(H\alpha, 20000\ \mathrm{K}) = 1.83 \times 10^{-25}$ erg cm^3 s^{-1}

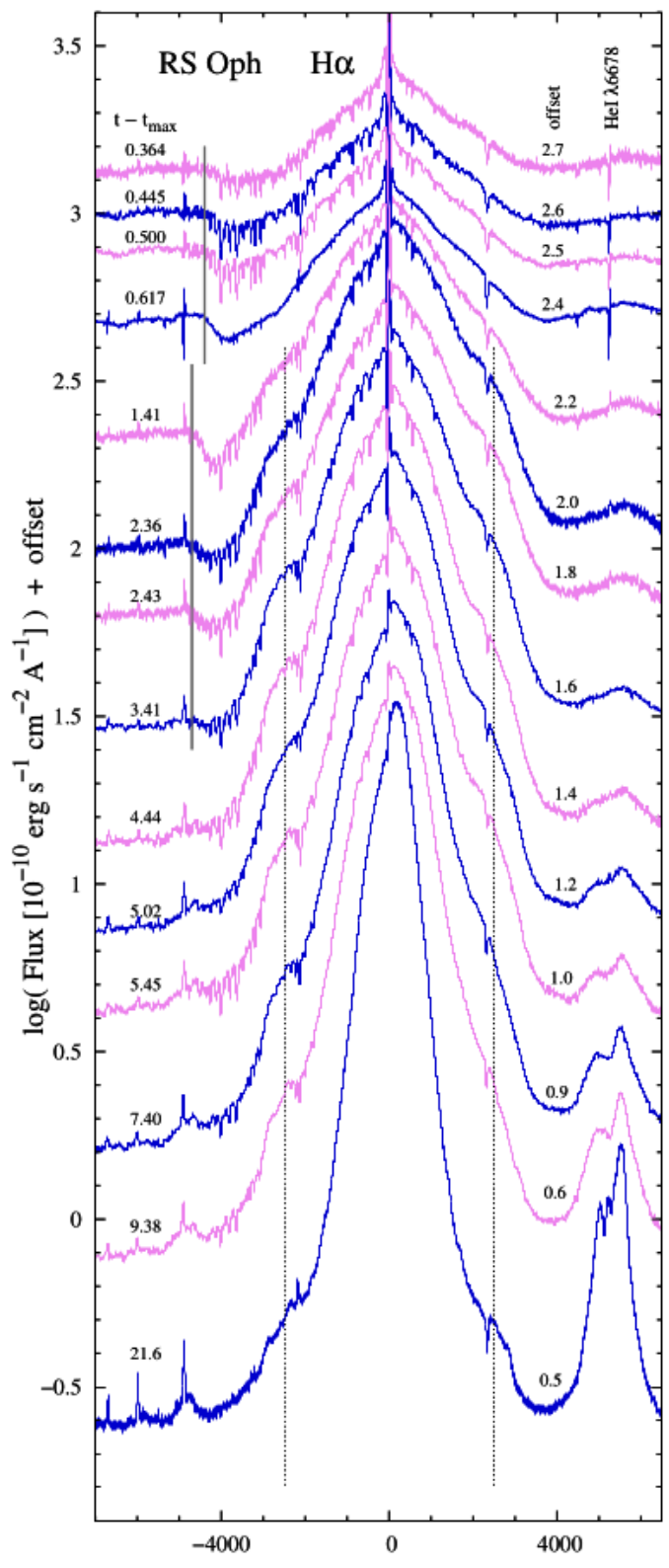
- The mass of the ionized ejecta:

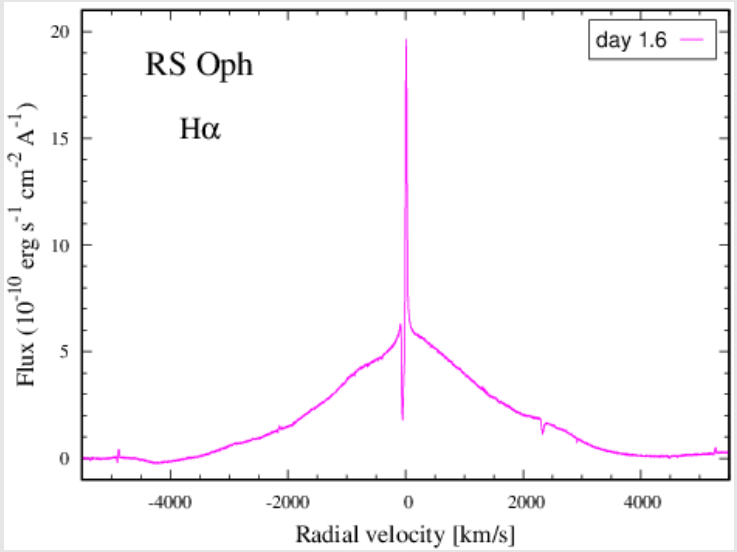
(from d-0.13 to SSS phase – wind stops)

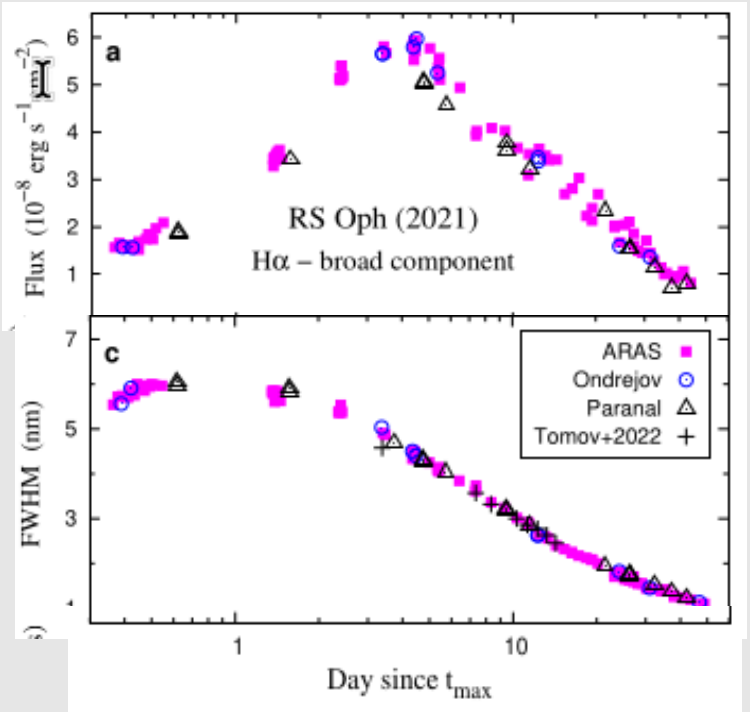
$$M_{neb} = \int_{0.13}^{42.6} \dot{M}_{WD}\, dt = \sim 1.2 \times 10^{-5}\ M_{Sun}\ yr^{-1}$$

Method: Skopal et al. 2017, A&A, 604, A48 (Appendix C)

Evolution of the Hα line: Broad & narrow components







Broad component is from the ejecta:

FWZI ~ 8000 km/s
Day 3–4: absorption at ~ -4500 km/s

$F\alpha \propto n^2$, $n \propto dM/dt$,

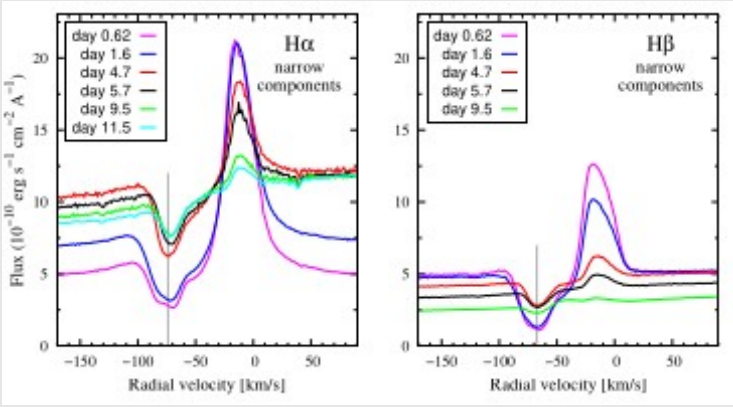
Expansion: $n \propto v_\infty^{-3}$

→ lengthening of the recombination time (∝1/n),

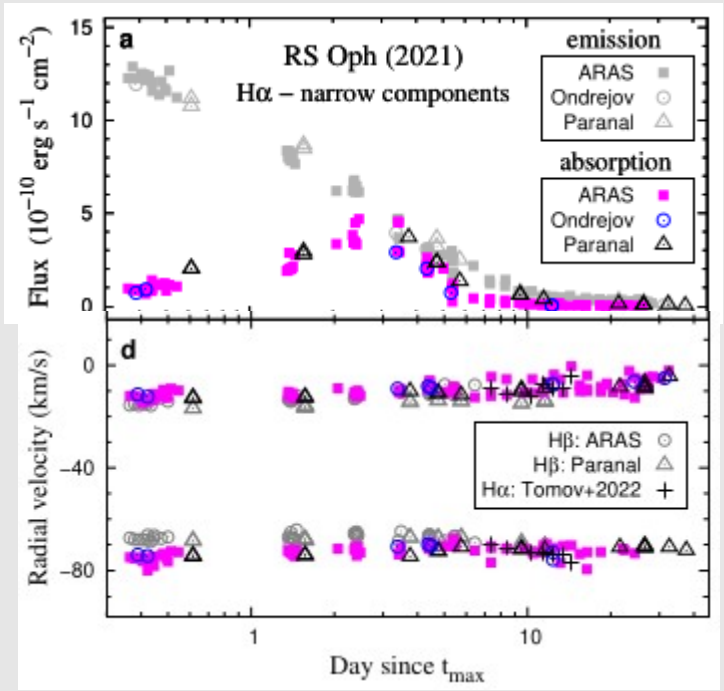
→ reducing total emission per unit time.

Narrow components are superposed on the top of the broad emission

- Observed from the very beginning of the eruptions
- Origin in the surrounding wind environment ionized by X-ray/UV flash (Munari, 2025)



Mt. Paranal. ESO-VLT:
R ~ 100,000.
Non-P Cyg profile suggests a non-spherically symmetric distribution of the giant's wind with a reduced density in polar regions.

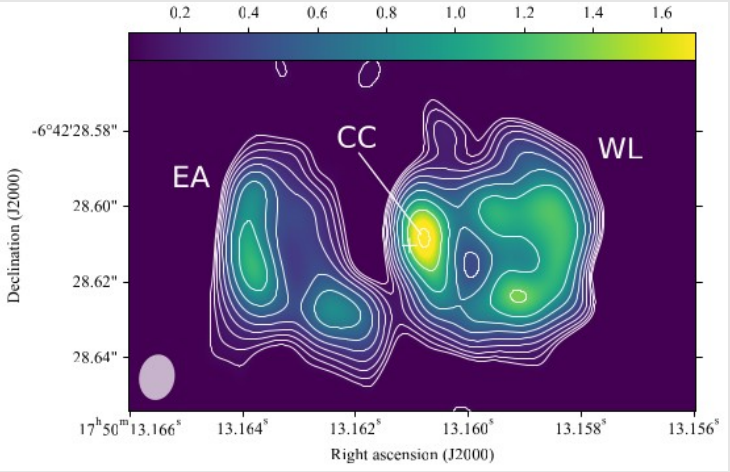


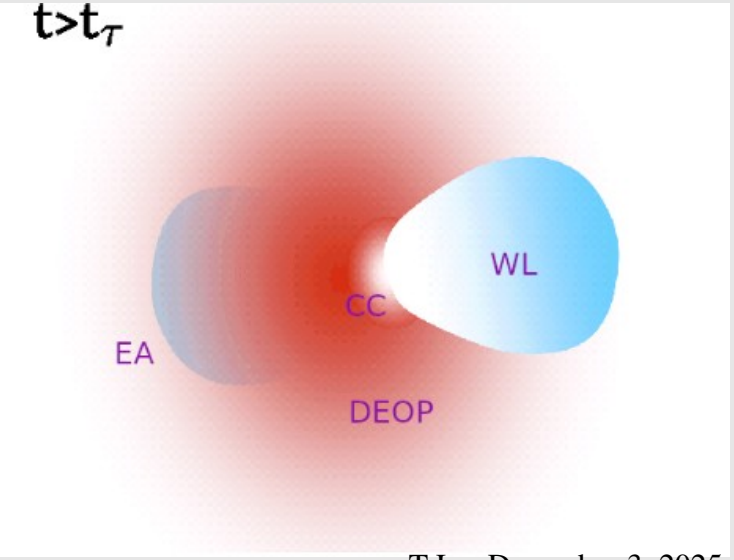
Evolution of narrow component profile (top), its fluxes and radial velocities.

X-ray/UV flash ionizes the surrounding wind until the optical brighte-ning, when the ionizing photons are absorbed by the ejecta.

v_∞ = 34 +/- 3 km/s

Radio observation at 5GHz on day 34.
Indication of a density enhancement on the orbital plane (Munari+, 2022).
Consistent with the non-P Cyg prof.





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Conclusion

– The presence of the stellar and nebular component of radiation in the spectrum of the ejecta revealed its biconical structure from the very beginning of the explosion.

– Around the maximum brightness, the WD pseudophotosphere had inflated to ~290 R⊙, cooled to ~7300 K, and its luminosity had greatly exceeded the Eddington limit. A strong nebular component with an emission measure of several times 1E+62 cm-3, requiring the presence of an ionizing source with a luminosity of several times 1E+39 erg/s had developed.

– The mass-loss rate was decreasing from its maximum of ~5×10^{-4} M⊙/yr on day 0.62 to ~2×10^{-5} M⊙/yr od day 43. The corresponding total mass ejected, Mej ~1.2×10^{-5} M⊙.

Thank you for your attention