Eruptive stars spectroscopy
Cataclysmics, Symbiotics, Novae

Eruptive Stars
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Supplement 1

Contents

The 2021 eruption of the recurrent nova RS Oph

A little bit sooner than expected, the symbiotic system RS Ophiucii produced a new nova event in August, 2021. The previously outbursts were recorded in 1898, 1933, 1958,1967, 1985 and 2006, with possible outbursts in 1907 (Schaefer 2004) and 1945 (Oppenheimer & Mattei 1993).

The spectra (about 1 hundred in one week) secured by the Team from resolution 500 to 30000 and daily echelle spectra are gathered in ARAS database: https://aras-database.github.io/database/rsoph.html

In this supplement, Steve Shore proposes a comprehensive description of the phenomena at work during this event in order to allow us to better understand the formation of the spectra that we obtain.

Of course, we undergo the monotoring and we do not forget T CrB another symbiotic recurrent nova which could produce a nova event any time from now.

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S. Shore

"We acknowledge with thanks the variable star observations from the AAVSO International Database contributed by observers worldwide and used in this letter."
Kafka, S., 2020, Observations from the AAVSO International Database, http://www.aavso.org

Yes, this is a nova.
And yes, it's an explosion.
That's where the similarity with your normal experience ends.

1. Background

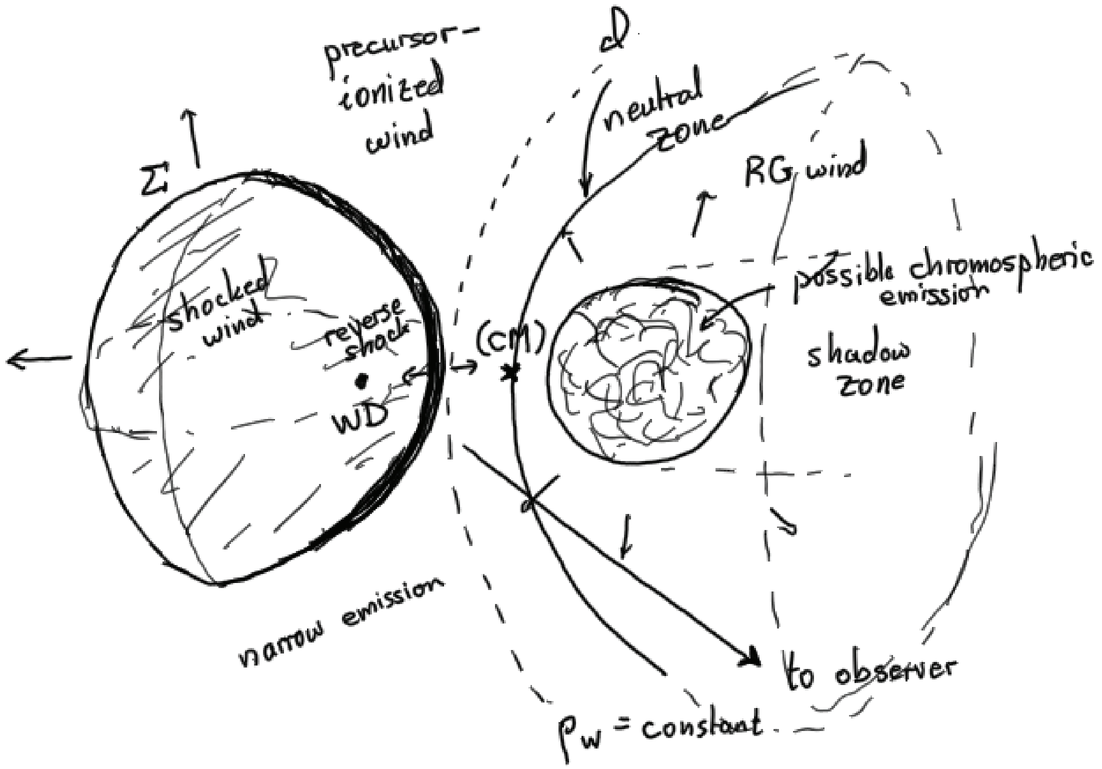
This small group of recurrent novae, what I'll refer to as the symbiotic-like recurrent novae (SyRNe) to distinguish them from *symbiotic novae*, are symbiotics with a difference. While the giant and long period components are almost identical to the classical symbiotics, the mass gainer is not.

In most ssymbiotics, the white dwarf (WD) is relatively low mass, certainly less than 1 $M_\odot$. This says the evolution of the companion went through, at most, helium burning before losing the envelope an exposing the core. Otherwise, as with any degenerate star, the accretion process on the WD is the same and to the same end. The accumulation takes place mainly from the wind of the giant, and, as you know from observations, the resulting hard emission ionizes and excited he gas in the environment.

Hence, except for lines formed in the immediate vicinity of the WD, the emission lines from the symbiotics is exclusively from the ionized region formed within the slow wind of the giant. That these lines don't vary much, or only over relatively long times (months, years) is the signal of the formation process. These lines arise from a stable (or nearly so) equivalent of a dense H II region, like that which you'd find around birthing massive stars. The winds are sufficiently optically thick that the Lyman lines can populate the lower levels of the Paschen and Balmer lines so you have composite profiles: the self absorption of the wind and the emission from the broader, ionized gas from recombination in photoionization balance.

That's the overall picture of the SyRNe when the system is in equilibrium,. Except for the mass of the WD, there is little if anything to distinguish one of these fro any other similar symbiotic. But mass is what makes the difference.

Accretion leads to a nova in these systems *precisely as it does in any close, mass exchanging binary when the critical pressure is reached in the WD envelope*. It happens, because of the previous evolution of the component stars, that the WD is massive, nearly at the upper mass limit for the degenerate component (what you know as the Chandrasekhar limit, although it's not quite that high); suffice it to say that the degenerate gainer is more than 1 $M_\odot$ and likely a CO composition, not helium, compact and otherwise accreting from a nonspherical wind. What drives the accretion is actually of little importance except for the amount of material carried toward the WD and the efficiency of the accumulation. If captured gravitationally from the wind, the rate of accretion is strictly limited by the velocity of the wind and the orbital deflection by the binary. If instead, the giant happens to approach or fill its Roche volume, then you can have an analog of classical cataclysmics (except with am orbital period of years to decades instead of minutes to hours). The accretion mechanism is less important than the rate, which determines how long it takes to build up a critical layer that initiates the thermonuclear runaway so familiar from discussions of novae, and that ultimately produces an explosion that ejects a significant part of the accreted gas.



Model for the nova event in RS Oph

So far, except for the details of the components, there's virtually nothing that distinguishes these novae. As recurrents, it puts them on the massive end, and as massive it puts constraints on the system's previous lifetime, but that's about all. What's different here is that all of your experience interpreting the resulting spectrum and understanding the dynamics and energetics of the ejecta go out the window.

Classical systems are isolated and clean. While there certainly remains circumstellar gas from windy phases of the cataclysmic system and previous ejecta (e.g., the garbage remaining around some rapid recurrents) these play little role in the energetics. A flash photoionizing pulse from the start of the TNR or the envelope expansion is possible, this has been discussed by Munari and others as a flash that the recombines (you'v seen this in several recent novae, a narrow component that appears in the first days and then disappears, having far lower velocity width than the main ejecta lines). The densities are low for this circmstellar gas and it is rather far away, the timescale for its first appearance is the light travel time and that's usually days or even longer. It's completely different here so let me explain.

2. The shock and its effect

I'm going to take a very biased foundation but there's little changed if you talk about multiple ejections or even winds but that's no matter here. What is important is that spectral formation in freely expanding ejecta of classical novae (CNe) depends only on the irradiation of the gas by the central source, aside from any internal shocks because of the range of velocities of individual fragments imposed at the time of the explosion. The highest velocity material is also at greatest distance and lowest density, although the details are not important for the main differences. This front gas is actually invisible very rapidly, as soon as it turns optically thin (which also has to do with the passage out of the Fe-curtain phase with all of the recombination wave effects you know from the early and visible maximum photometric intervals).

The acceleration of the absorption lines is due to the advance of the recombination as the curtain grows and there can be oscillations in line profiles and velocities if the central source should vary, as we know from e.g., ASASSN 17hx.

The alternations are actually the demonstration of free expansion and a clean environment. When the ejecta become sufficiently transparent and low density, recombination is inhibited and if the central ionization turns off or drops, the ionization state of the gas is permanently frozen in whatever condition the last irradiation produced (this is the ``frozen-out'' state, which can persist almost forever if the densities are low enough). The expansion is controlling how the ambient density drops so if the central source is off the recombinations become progressively slower. If any ion has a longer recombination time to a lower ion than the timescale for the ambient density to decrease, then the recombination is expansion controlled and the ionization state freezes out with the emission line intensity gently falling but never reaching zero. This is neither collisionally nor photo-ionized and very far from equilibrium but it's the eventual state of the ejecta.

Not so for the SyRNe.

The ejecta are a piston slamming into a background whose density is comparable to that of the ejecta themselves. This means the ejecta are actually their own heating mechanism. Compression at the front, which depends on the state of the wind gas, raises the pressure and density, hence the temperature, of the post-shocked gas to a fair fraction of the kinetic energy per unit mass of the ejecta.

For CNe, we know the ejection velocities are at least a few 1000 km/s, so if that is a sort of lower limit for these shocks they have a Mach number of at least tens to about 100 and the temperatures can reach 10-100 MK. At such temperatures, the gas is a very (!) poor radiator (think of what lines might be available to cool this) and the expansion is essentially adiabatic. That doesn't mean there isn't a luminous source, just that it's not as efficient as for classical novae.

This is the most important difference I can emphasize:

You only see the part of a flow or ejecta or remnant that can radiate in your bandpass and the spectrum displays only those states that have transitions in your spectral window. If the lines can't form you don't see them.

If the gas reaches so high a temperature that the only emission in the optical and IR band from the post-shocked gas is continuum, that's all you'll see. So to talk about the acceleration or deceleration of the shock is a very complicated affair. In the compression zone, the Balmer and He I lines can show a terminal velocity at the shock itself, much as you would see from simple compression in a nuclear blast. The emission line would, on the other hand, arise from the whole cooling volume, until the gas is in free expansion there is too much heating for the emission lines to dominate the energy losses. In free expansion, ejecta of CN undergo recombination. Here that isn't possible, there's a massive, hot bubble left within the wind that's being excavated by the expanding piston.

More to the point, this whole environment resembles a thermonuclear atmospheric test. I urge you to watch and carefully study the films of atmospheric and surface thermonuclear tests from the 1950s, especially the Castle Bravo blast. Unlike the explosions in space, where individual fragments form from instabilities at the front, the expanding shock front here is a material front but not necessarily the same as the ejecta. That's an essential distinction from the CNe - here the shock is a compression zone and visible - always - as long as there are sources against which it can absorb. The Lyman continuum and lines are collisionally populated, 10 or 11 eV is nothing for these ejecta in the collision portion of the front, and that produces the absorption on the Balmer and higher line series.

But there's another feedback from this event: the hot gas, which is a strong X-ray and UV emitter, is not impeded by the shock front itself and the expanding bubble irradiates the wind ahead of the shock. This is not the same as the flash effect of an initial breakout or similar event. It continues for as long as the ejecta are plowing through the wind and only ceases when the density has fallen sufficiently, and its velocity sufficiently reduced, that the shocked gas no longer dominates the ionization state of the wind.

Additionally, during this stage, as the ejecta are clearing out the cavity of the wind and also changing the ionization, the supersoft source from the continued nuclear burning on the WD appears and adds to the ionization balance.

In previous RS Oph outbursts, this turned off around the same time as shock ``breakout'' but that may be fortuitous. Regardless, the gas then recombines in the red giant wind, as known from the later time analyses of V407 Cyg, and the structure of the wind, shadow zones (yes, there is a giant in the way and a part of the circumstellar gas is actually shadowed), accretion wake, and continued mass loss eventually relax to the pre-outburst state. That takes some time and since the systems are wide there can even be hight travel time effects (as seen in the ionization of the environment around SN 1987A).

3. Extending your worldview: dirty environments and photo-processing

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There are two more essential differences between these systems and Classical Novae.

T*he mass of the ejecta is not constant*, matter overtaken by the shock is accelerates and incorporated within the gas, so both the mass of the emitting gas (what you see) and its composition change in traverse of the wind. Nothing like this happens in classical novae! If the giant has anything like solar composition, within about a week (for RS Oph) the ejecta have accelerated and accumulated about their original mass and the abundances have been altered.

The absorption lines you have from the wind seen against the ejecta and WD, and the pre-outburst spectra of the system, are superb constraints on the composition of the gas accreted onto the WD but tell you little about the nucleosynthesis because of this contamination.

The same holds for the emission lines. As the precursor - the ionization front driven by the hard post-shocked gas emission - advances through the wind, absorption lines flip over into emission and you can see this march of the front over time.

Then, after the end of the event, you will see the absorption lines reappear as the wind repairs itself once the source is turned off. This is the second essential difference: when lines disappear during this early stage it may *inot* be from recombination - the ionization is powered and increasing as long as the shock expands.

Thus, although you had He I and Fe II and so on during the first stages of the expansion, their disappearance can also mean that you have passed He II and are not yet recombining.

For instance, at the start there were very strong P Cyg profiles from the wind. Those weakened from Aug. 8 through Aug.13 and disappeared by Aug 14. The ions do not have to have recombined, instead you have ionized all of the Fe^{+} the same for most of the species you'd expect to see here, e.g., Si II 6347 Å etc.

The O I transitions are especially interesting since they are from gas at higher density and possibly ionized; there was no Na I emission this time in the RS Oph spectra. It will be interesting to follow the components on Na I to see how they change in the next weeks, the same for any of the Ca II H & K lines. Collisional excitation and ionization, far from equilibrium (hence, *not coronal conditions*) will dominate much of the line formation from the shock and the precursor will be traceable by the forbidden lines from Fe II and other low ionization species, and especially from their line profiles.

So what you have in all of your data are multiple regions

So what you have in all of your data are multiple regions, very distinct in their signatures but all mixed together in space and velocity.

The shock is the main driver and why these are essential for understanding a related but different event: the expansion of a supernova remnant in a molecular cloud and the shock-produced very high energy emission from GeV and higher energy electrons and protons. In effect, in miniature, RS Oph replicates the events thought to seed the Galactic pool of cosmic rays. The accelerated electrons radiate synchrotron, it's inevitable that some (even weak) magnetism is imbedded in the red giant wind[1].

Never forget that the giant is ``red'', hence possessed of a deep convective envelope.

Even if not so organized as to show surface spot activity, and it doesn't appear that these systems do, the weak fields will nonetheless be compressed and amplified and the tangles will trap electrons as they diffuse away from the shock. Even if only modestly accelerated, they will produce nonthermal emission.

The detection, from V407 Cyg on, of strong γ-ray emission (at MeV) and now at GeV from H.E.S.S., shows the promise of these ``really good novae'' (to quote the Sidney Harris cartoon so beloved of Starrfield) to break open the ambiguity of the acceleration mechanism responsible for the *Fermi* high energy continuum emission in the interstellar medium.

But that is for the next instalment.

[1] 1Never forget that the giant is "red", hence possessed of a deep convective envelope. Even if not so organized as to sow surface spot activity, and it doesn't appear that these systems do, the weak elds will nonetheless be compressed and amplied and the tangles will trap electrons as they diuse away from the shock.

ARAS Spectral Database: Submitting and using spectra

ARAS Spectral Database:
http://www.astrosurf.com/aras/Aras_DataBase/DataBase.htm

The ARAS Spectral Database is the result of the commitment of many observers who voluntarily make a substantial investment of their time and money to carefully acquire, process and share their spectra.

Submitting data to the database

While a basic validation check of submitted spectra is carried out prior to adding them to the database, it is primarily the responsibility of those submitting data to verify the quality of their spectra.

Detailed instructions on how to process and submit spectra to the database are given here:
Link to instructions (*in construction*)

Conditions for use of the data are described below. By submitting data to the database, observers acknowledge and accept these conditions of use. Ownership of data in the database remains with the observer.

Conditions for use of data from the database

This is an open database and in order that we can maintain this status, we expect those who make use of spectra from the database to abide by the following conditions:

1. The ARAS Spectral Database must be acknowledged in all publications which make use of spectra from the database by reference to the following publication:
http://articles.adsabs.harvard.edu/pdf/2019CoSka..49..217

2. Reference to the database should use the following link:
http://www.astrosurf.com/aras/Aras_DataBase/DataBase.htm

3. The names of observers whose spectra are used in the analysis must be included in the Acknowledgements section of the publication.

4. If the publication includes, or is linked to, a table of observations, it is strongly encouraged that this should include the names of the observers.

5. It is the responsibility of the lead author to consider including observers as co-authors if they believe their observations have made a substantial contribution to the analysis.

6. Authors are strongly recommended to inform the ARAS Team via the following email address prior to any publication using spectra from the database to confirm the Acknowledgement is compliant with the conditions of use: francoismathieu.teyssier@gmail.com

François Teyssier (FR), David Boyd (UK), Forrest Sims (US)

Eruptive stars spectroscopy
Cataclysmics, Symbiotics, Novae

Spectroscopic monitoring of eruptive stars (e.g. symbiotic binaries, classical novae) by amateurs around the world, in both the northern and southern hemispheres, is a fundamental activity of the ARAS (Astronomical Ring for Amateur Spectroscopy) initiative. The group of volunteers demonstrates what can be accomplished with a network of independent, very small telescopes (from 20 to 60 cm), furnished with spectrographs of different resolution, from 500 to 15000, and covering the range from 3600 to 9000 Å. The observing program concentrates on bright symbiotic stars (67, to date) and novae (41, to date). The main features of the ARAS activity are rapid response to alerts, long term monitoring and high cadence. A part of the program involves collaborations based on requests from professional teams (e.g. CH Cyg, AG Dra, R Aqr, SU Lyn, T CrB) for long term monitoring or specific events.

Submit your spectra:

Please :
- respect the procedure
- check your spectra BEFORE sending them

Resolution should be at least R = 500

1. reduce your data in accordance with standard procédures (notably offset, dark, flat, correction of atmospheric and instrumental response)
2. the header must be compliant with BeSS file format
3. name your file as: _novadel2013_yyyymmdd_hhh_Observer
   Example: _chcyg_20130802_886_toto.fit
4. send you spectra to francoismathieu dot teyssier (at) gmail com (dot) com for inclusion in the ARAS database and a copy to arasdatabase@gmail.com for double check by David Boyd and Forrest Sims.

Conditions for use of data in publications

This is an open database and in order that we can maintain this status, we expect those who make use of spectra from the database to abide by the following conditions:

1. The ARAS Spectral Database must be acknowledged in all publications which make use of spectra from the database by reference to the following publication: http://articles.adsabs.harvard.edu/pdf/2019CoSka..49..217

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5. If the publication includes, or is linked to, a table of observations, it is strongly encouraged that this should include the names of the observers.

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Your observations, taken with higher cadence than usually followed in the literature will be key to understanding this in a broad range of systems.

S. Shore, 2015

Your dedication, interest, and persistence are continuing gifts to the community, to future generations who may eventually be able to understand these phenomena because of the precision and care of your contributions. You may think it's just one spectrum, or one datum, but without the history any inferences are tentative at best and misleading at worst.

S. Shore, 2020

… the presented results showed also the importance of professional/amateur collaborations. ARAS Group is a perfect example that such collaboration can be very successful and can bring important results. Thanks to amateur photometric and spectroscopic data, we are now able to monitor the evolution of symbiotic systems on timescales which were not previously available.

R. Gàlis& al., 2019

We are grateful to all of the amateur astronomers that contributed their observations to this paper. In particular, we are thankful to members of the ARAS group for their wonderful work.

K. Ilkwiecz & al., 2015

High cadence of both photometric and spectroscopic observations as provided by AAVSO and ARAS databases allows a detailed mapping of usually fast events of outbursts

A. Skopal, 2019

The Letter is prepared by François Teyssier (FR), David Boyd (UK), Forrest Sims (US)

Download previous issues of the Eruptive Stars Information Letter:

http://www.astrosurf.com/aras/novae/InformationLetter/InformationLetter.html

The letter in the SAO/NASA Astrophysics Data System

https://ui.adsabs.harvard.edu/abs/2019ESIL...43...19T/abstract

ARAS database:

http://www.astrosurf.com/aras/Aras_DataBase/DataBase_EruptiveStars.htm