X-rays from RS Ophiuchi's 2021 eruption: Shocks in and out of ionization equilibrium

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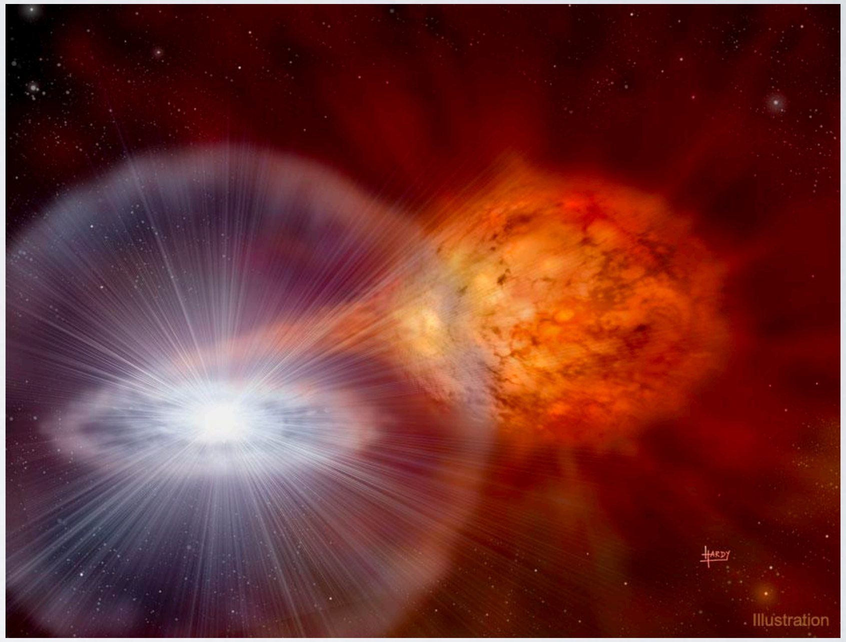
RS Ophiuchi

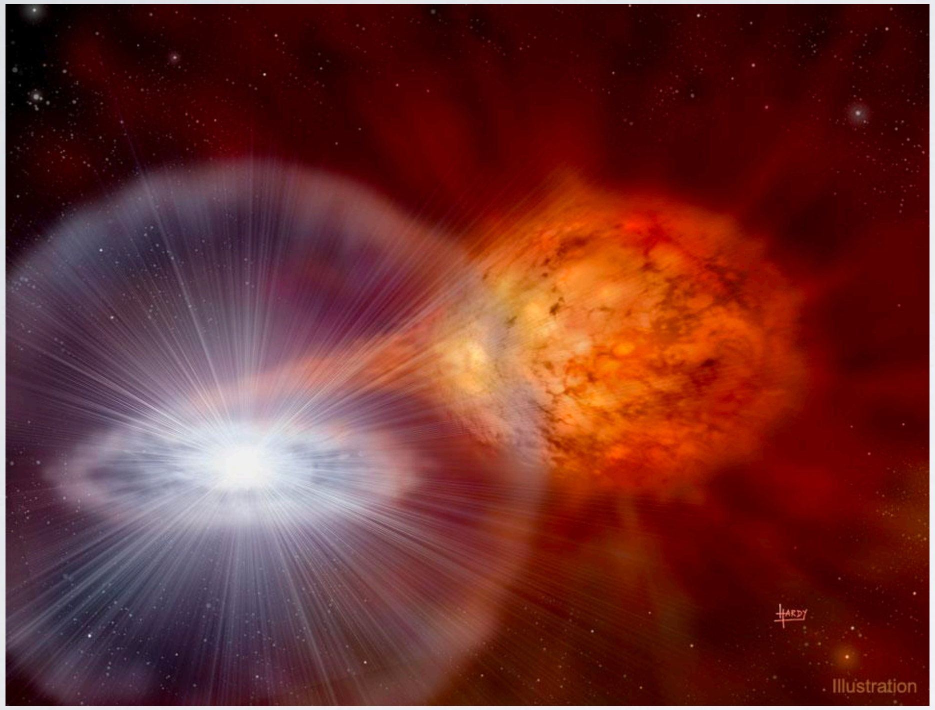
- The recurrent nova consists of a massive WD and RG donor star in a binary orbit of 453.6 days.
- Nova eruption every ~15 years when the accreted matter undergoes thermonuclear runaway on the surface of the WD.
- Releases large amount of energy which causes the ejection of accreted matter.
- The high velocity ejecta runs into the dense stellar wind from the RG, giving rise to X-ray emission from a hot shocked gas



Artist illustration of RS Oph

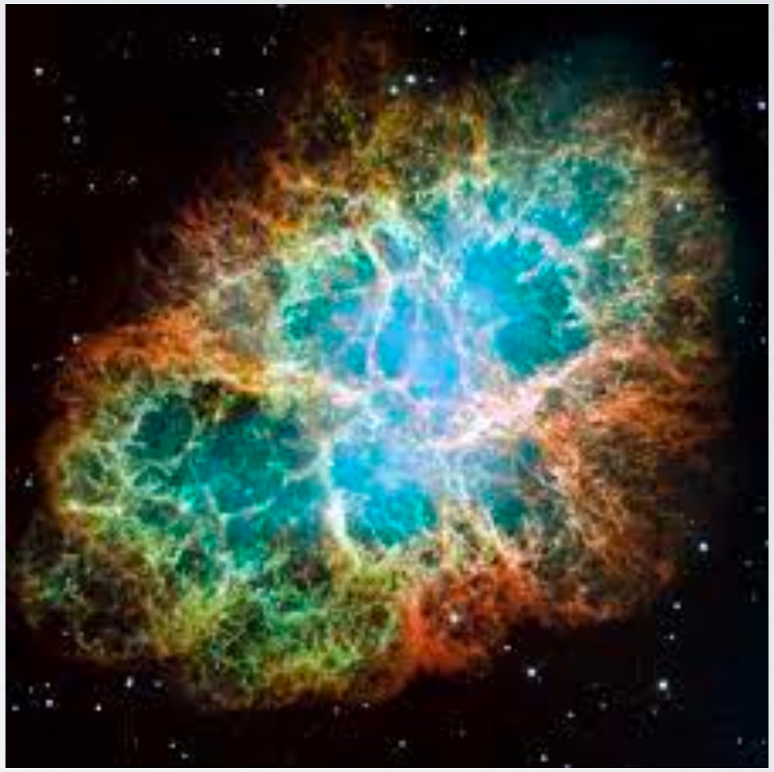
Analogues to supernova

RS Oph



- Shock waves interacts in days to months
- Ejecta expands into stellar wind of the RG star

Crab Nebula

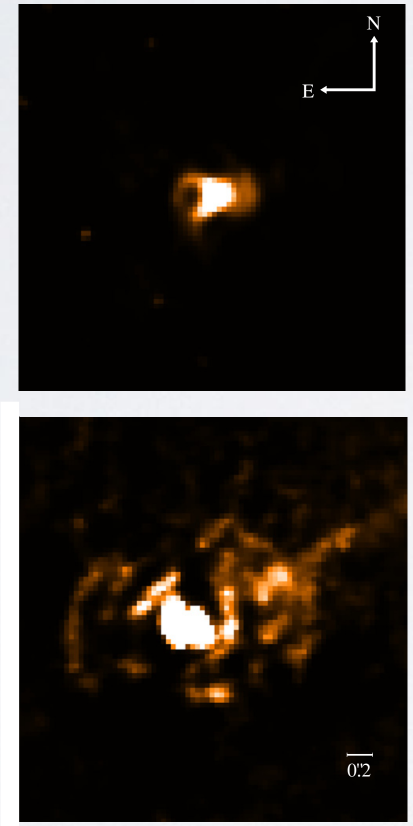


- Shock waves interact on years to decades
- Ejecta expands into the ISM

- Driven by shocks
- **Effects of non-equilibrium plasma are important**

Aspherical circumstellar environment

- RXTE PCA observations of 2006 eruption: The early hard X-ray emission originates from an outward moving shock wave moving into a spherical stellar wind (Sokoloski et al. 2006).
- HST and radio imaging after the 2006 eruption show that the circumstellar environment in RS Oph is highly asymmetric.
- Chandra detected an extended X-ray emission 3 and 5 yr after the 2006 eruption, which is consistent with a bipolar outflow (Montez et al. 2022).

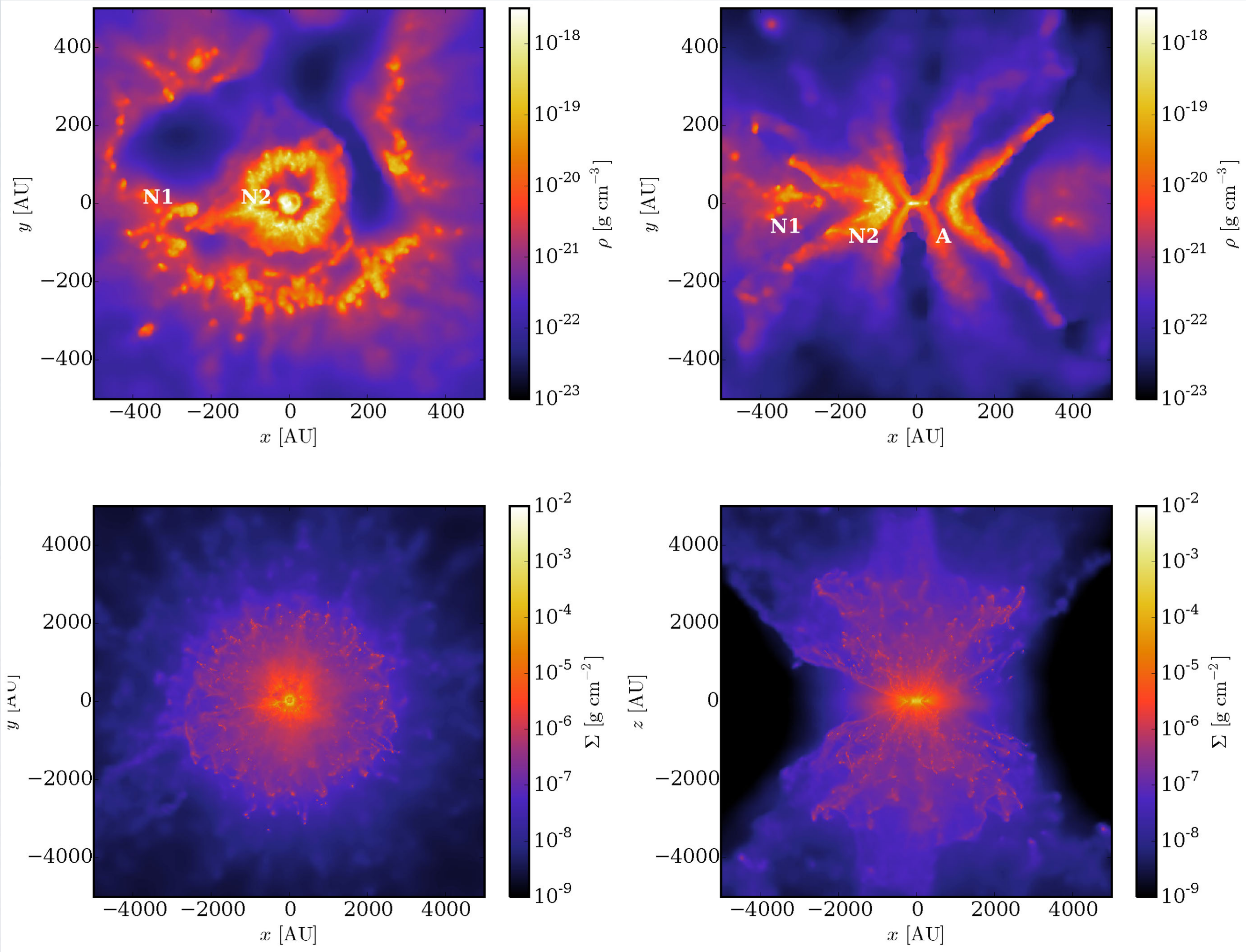


t=155 days after 2006 eruption

t=449 days after 2006 eruption

HST image of the RS Oph, showing double ring (Ribeiro et al. 2006)

Aspherical circumstellar environment



High density, slow moving equatorial ring (~200 km/s).

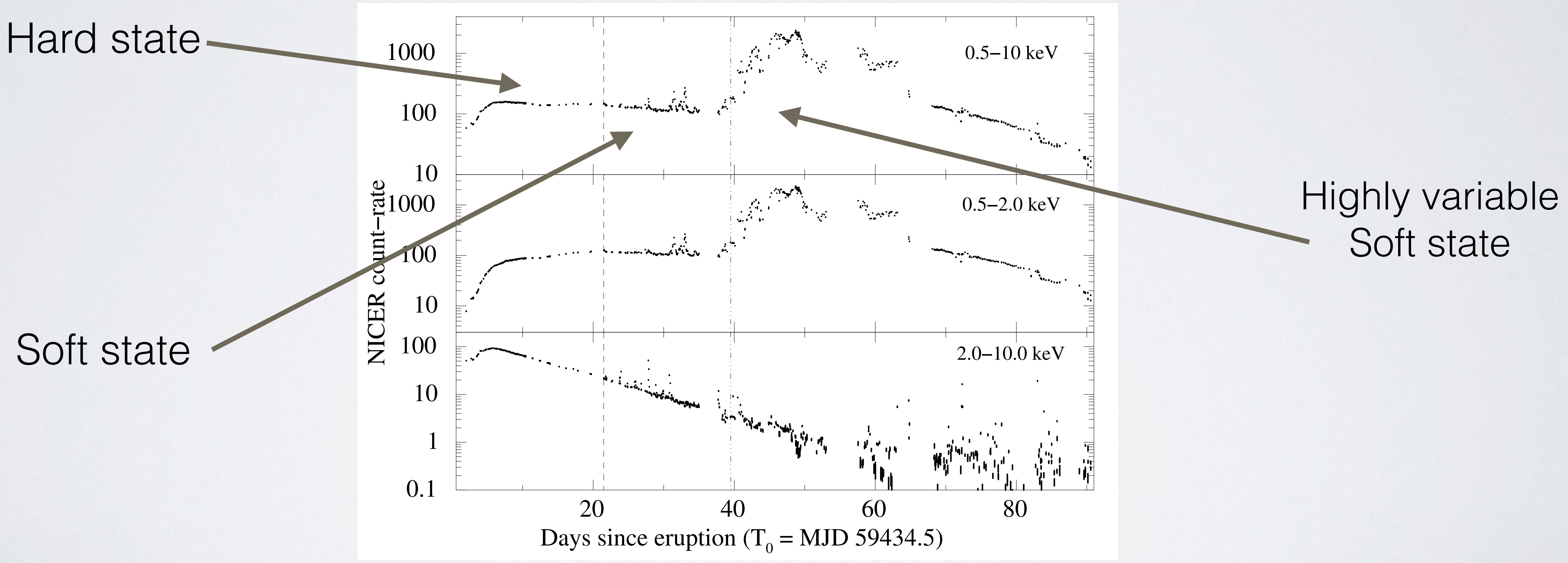
Presence of clumps

Low density, fast moving bipolar outflow (~4000 km/s)

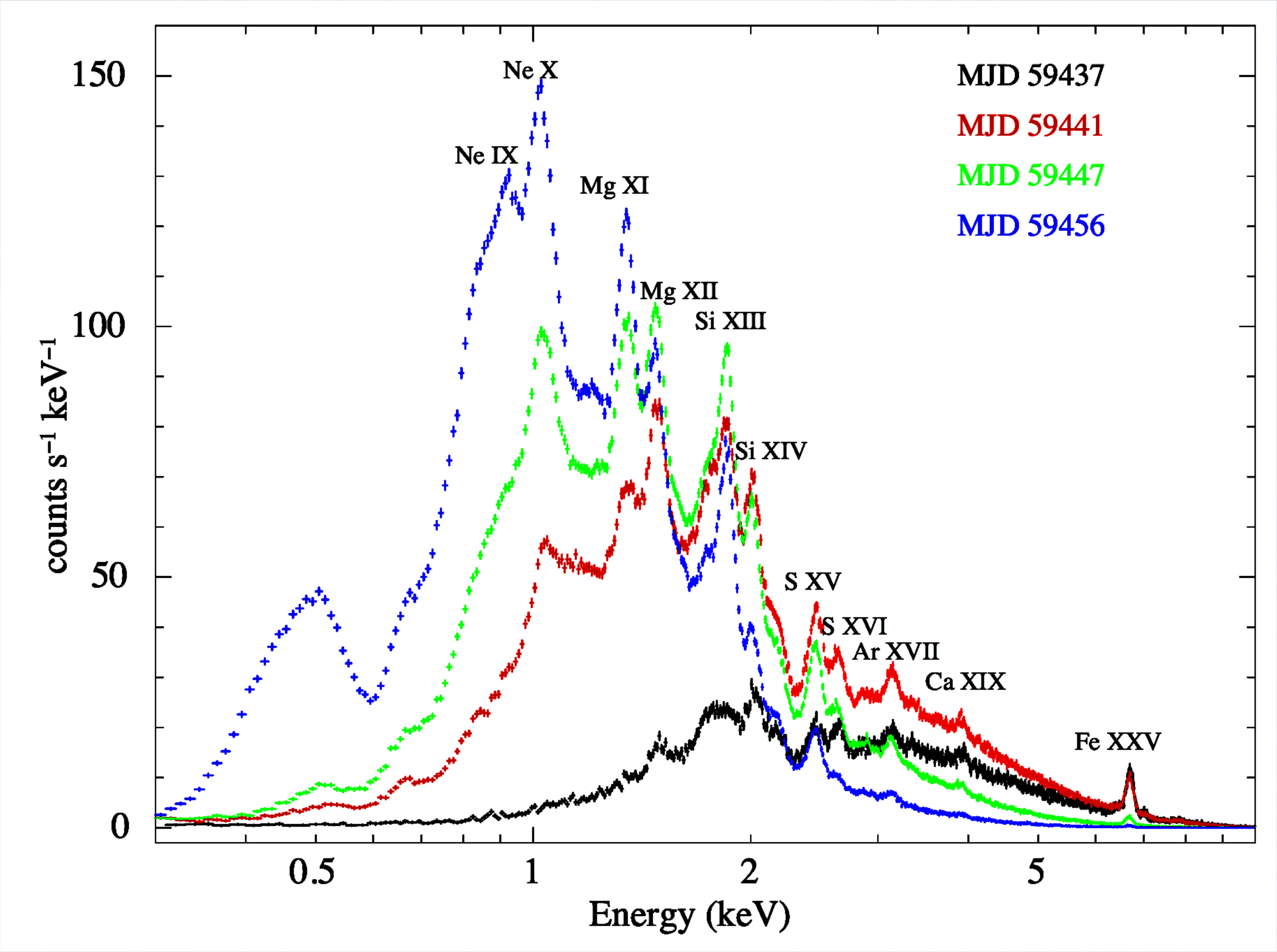
Simulation of the circumstellar environment around RS Oph (Booth et al. 2016)

2021 Eruption

- The recent eruption of RS Oph occurred on 2021 August 8. Detected in different wavebands of the electromagnetic spectrum.
- First Nova to have both detectable GeV and TeV emission, with Fermi LAT and HESS.
- NICER started daily monitoring campaign ~2 days after the start of the optical outburst.

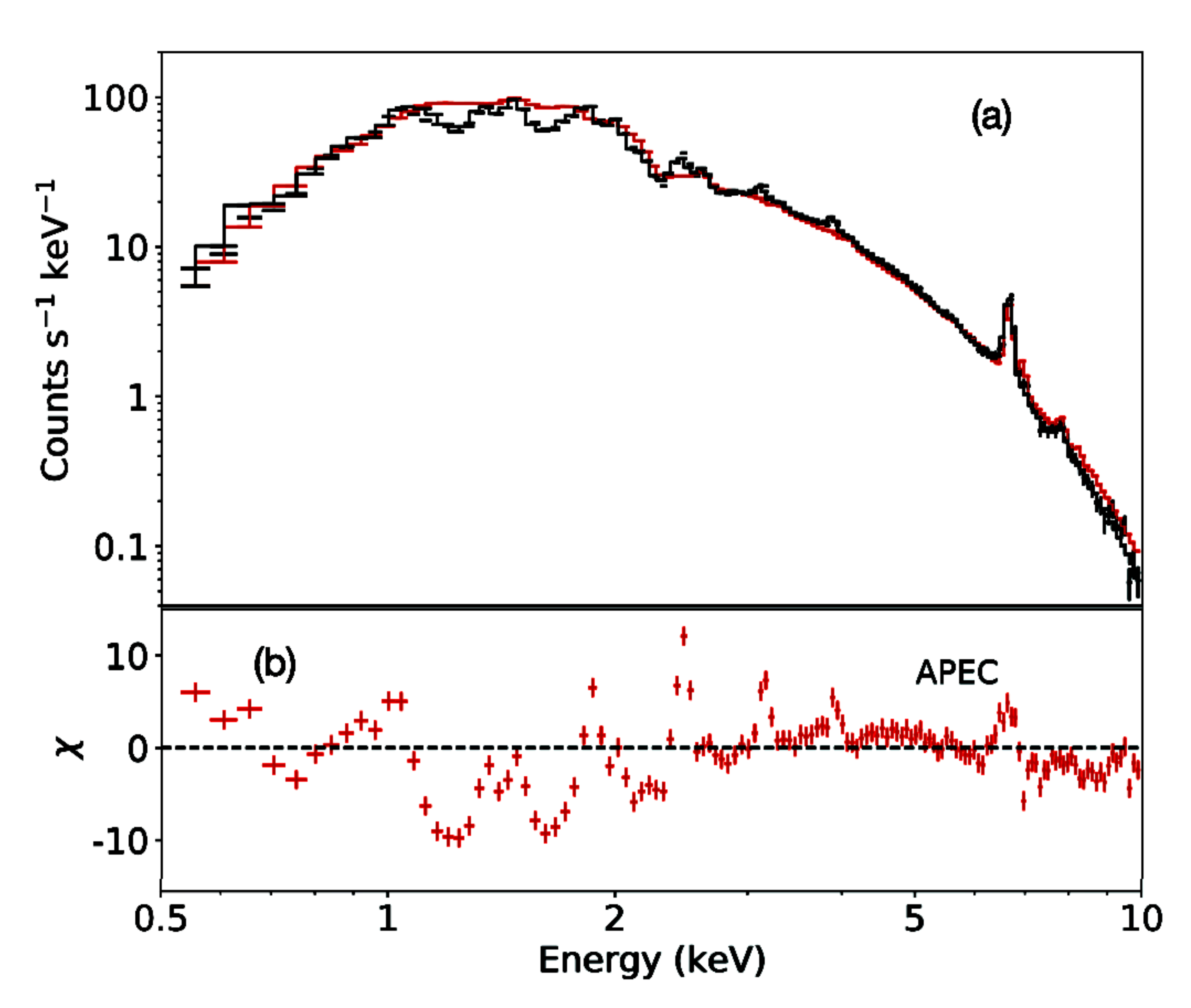


NICER spectra



NICER spectra constructed from observations taken during different days of the 2021 eruption, show evolution of the strengths of various emission lines from medium Z elements.

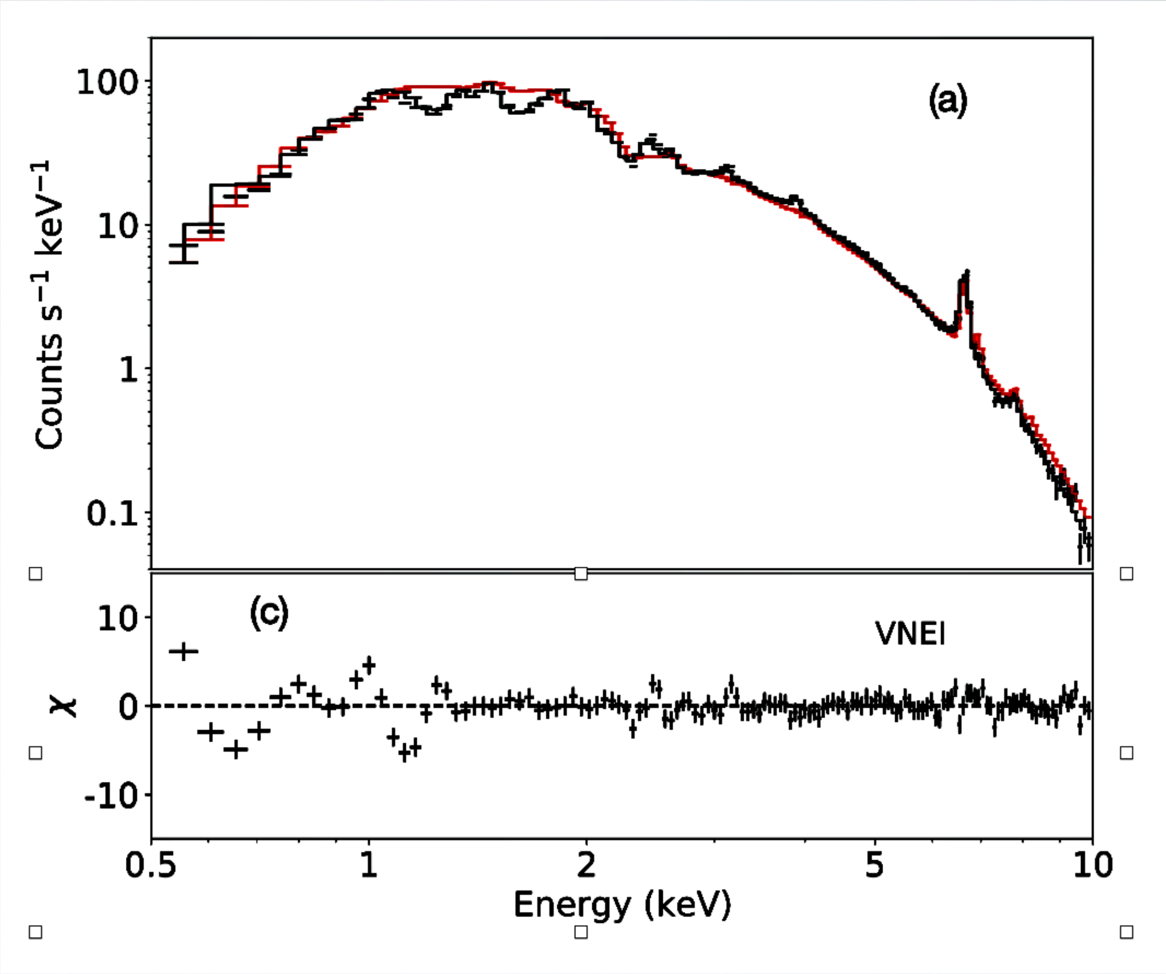
Collisional equilibrium plasma?



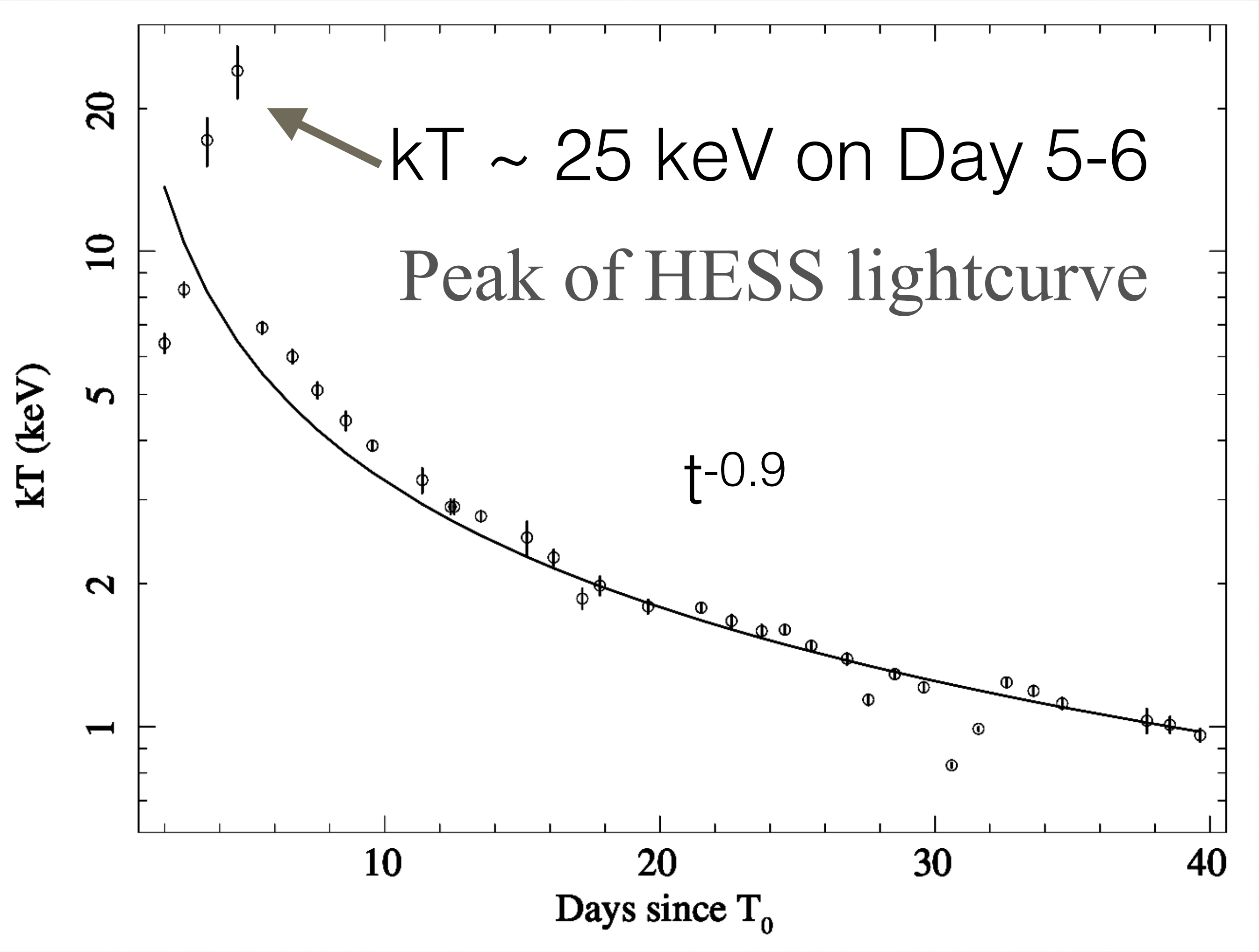
Single kT collisional equilibrium ionization model with a fully covering absorption model show significant residuals around the K shell lines from the medium Z elements like Ne, Mg and Si and at lower energies

Non-equilibrium Plasma Modeling

- NICER spectrum is fitted with non-equilibrium collisional plasma models, along with a partial covering absorption model for the variable RG wind.
- A grid of ***vnei*** models is constructed in xspec with different ionization timescales 10^9, 10^{10}, 10^{11}, 10^{12} in the units of s/cm^3
- The spectral model used in xspec : **Tbpcf*Tbabs*gsmooth*(vnei (10^9) + vnei (10^{10}) + vnei (10^{11}) + vnei (10^{12}))**



Non-equilibrium Plasma Modeling



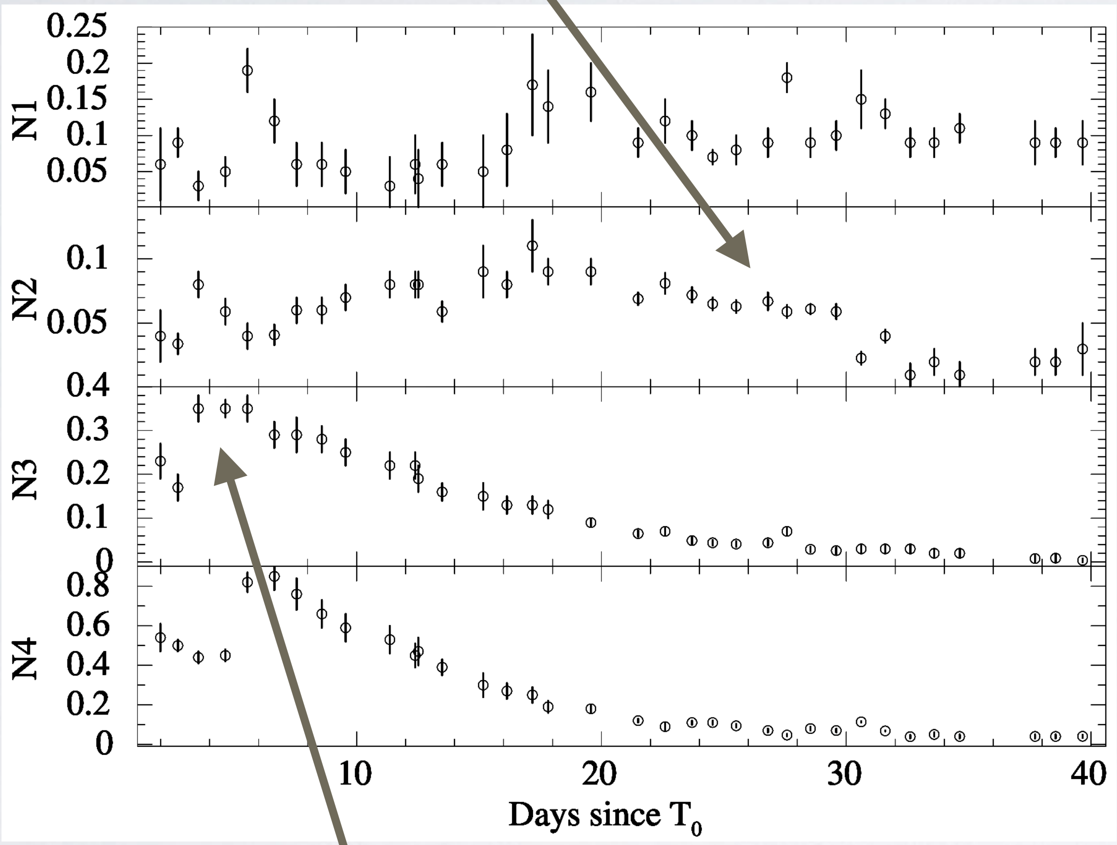
Increase in kT till Day 5-6 suggests interaction of the ejecta with a dense clump in the equatorial ring as predicted by Booth et al. (2016).

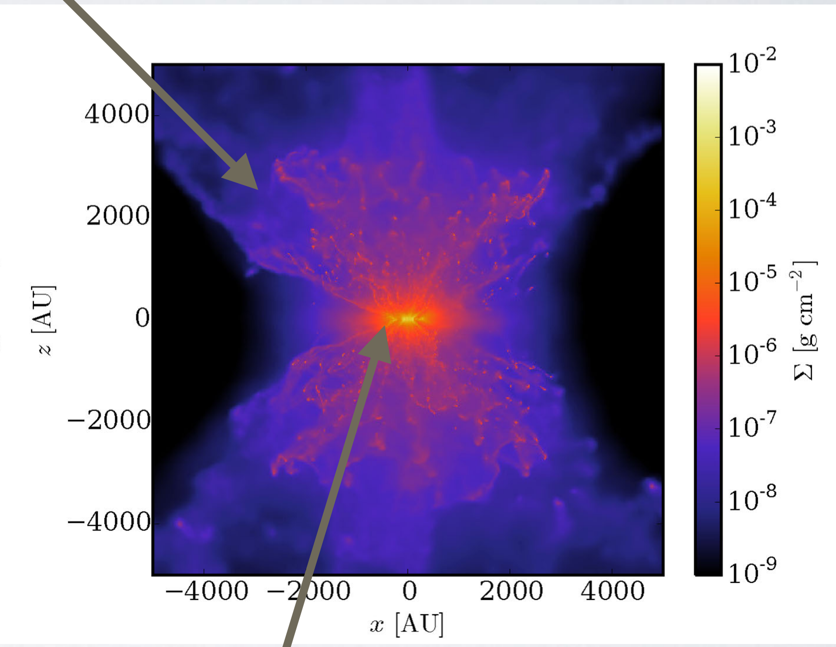
Brightening of RS Oph in 2017 in AAVSO light curves => Luna et al. (2020)

Two-zone model

Ionization timescales 10^9, 10^{10}, 10^{11}, 10^{12} in the units of s/cm^3

Later days => interaction with a less denser medium like bipolar outflows





Early days of the eruption => interaction with a denser medium like equatorial ring

Particle acceleration in multiple shocks => Diesing et al. (2023)

Summary

- Recurrent nova RS Oph provides a dynamical environment to study the interaction of the ejecta with the dense RG wind.

- Aspherical circumstellar distribution around RS Oph: dense equatorial ring and fast moving less dense bipolar outflows

- 2021 eruption of RS Oph was extensively monitored by NICER. A single kT APEC model with fully covering absorber fails to account for the emission from the medium Z elements and excess at lower energies.

- Grid like *vnei* models with a partial covering absorber are used to model the NICER spectra.

- The kT evolution peaks at Day 5-6 and declines with an index similar to a asymmetrical blast wave expanding into a stellar wind. The initial rise in kT could be due to an interaction with a dense clump of matter.

- The time evolution of spectral parameters => ejecta interacts with equatorial ring early in the eruption, and fast moving, less dense bipolar outflows later.

Thank you