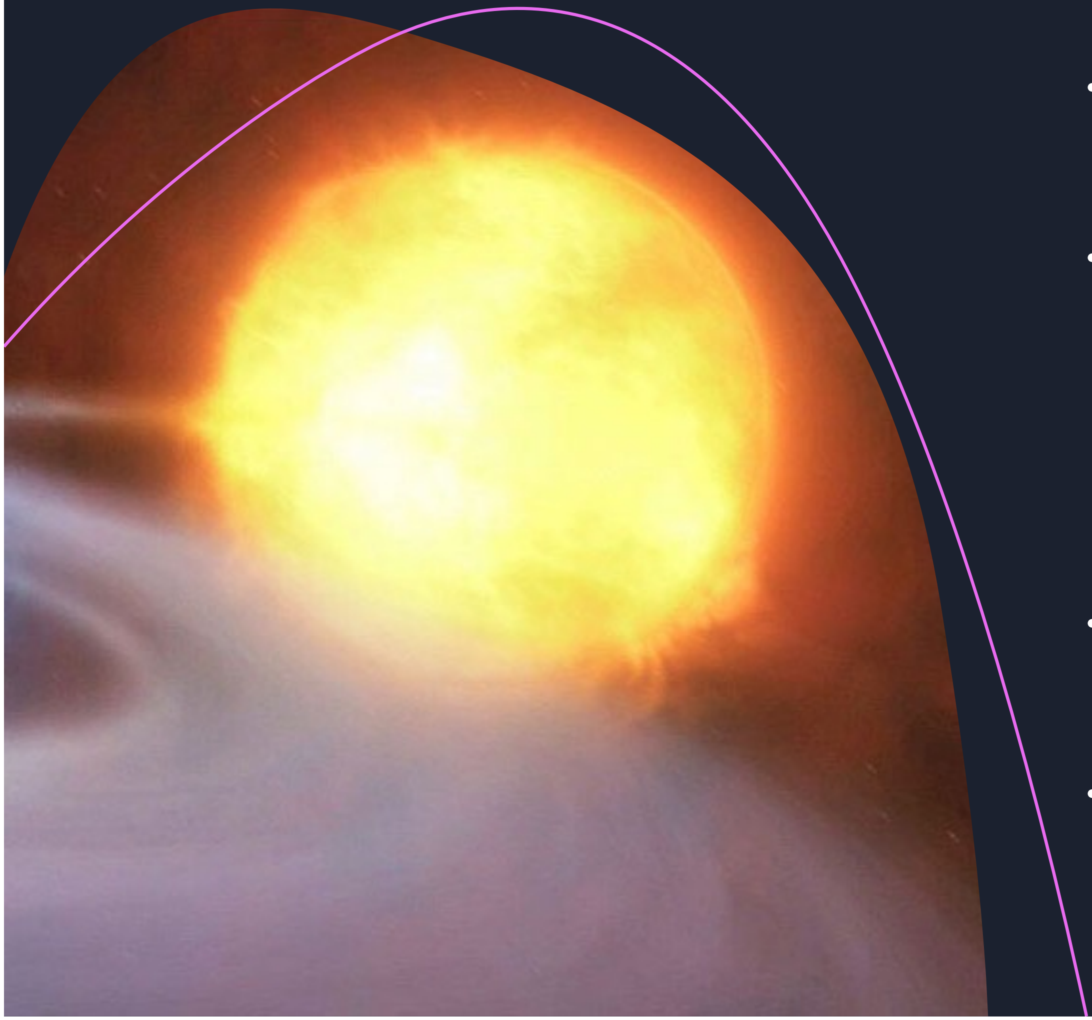
A legacy of Chandra: the intricate spectra of novae and supersoft X-ray sources

Marina Orio

Dept. of Astronomy, U Wisconsin

INAF-Padova associate

Many collaborators: Drake, Behar, Ness, Dobrotka, Rauch, Starrfield, Aydi, and others…



Why novae explode

- Novae are primarily due to a thermonuclear runaway (TNR) on an accreting and CNO-burning white dwarf (WD)
- The TNR does not seem to cause mass outflow, but after envelope swelling, a super-wind (thousands km/s) follows,   radiation pressure driven (in most models) or driven by effects due to the the secondary (frictional drag of orbital motion, or double envelope filling as in Shen & Quaetert 2022).
- Novae occur in cataclysmic variables (survived common envelope, orbital periods of ~2 hours to ~2 days) or in symbiotics (orbital period of years).
- The outburst duration and its timescales vary greatly, from ~2-3 weeks to 10 years, with most novae ejecting mass for several weeks or months.

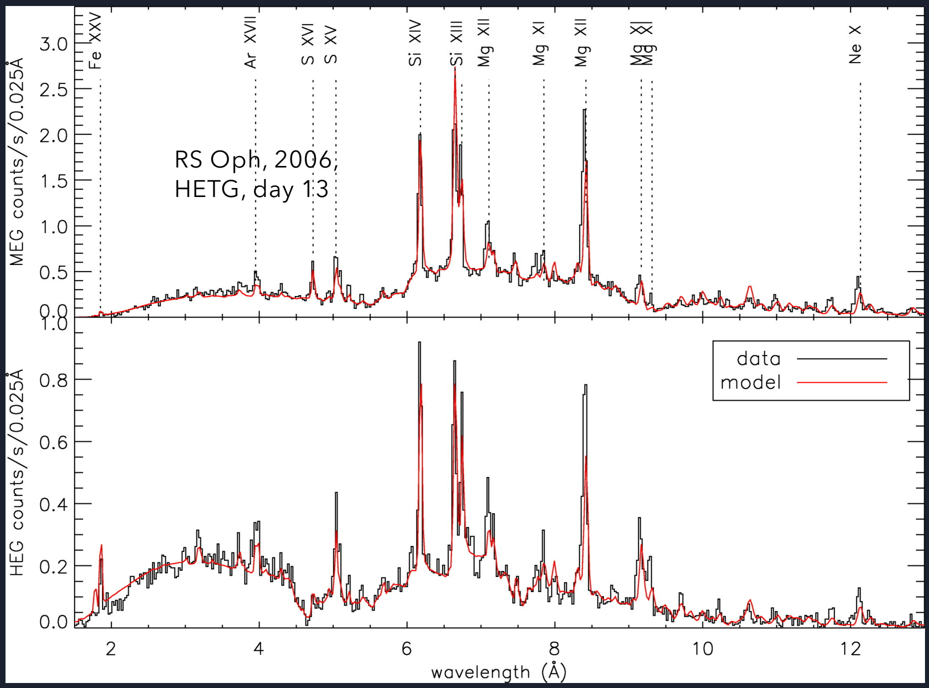
Why novae in outburst emit X-rays

- Short "fireball phase" of few hours during initial expansion, detected in YZ Ret (Koenig et al. 2022) and two Be star+WD nova candidate proposed to explain super-soft X-ray transients (< 1 keV, $L_x \geq 10^{38}$ erg/s)
- Shocks in the ejected shell, for colliding winds or wind+RG wind (or disk?) in symbiotics (even initial hard X-rays), $L_x \geq 10^{33}$ erg/s in CVs, $L_x \sim 10^{36}$ erg/s in symbiotic novae
- Hydrogen burning continues under the surface, atmospheric emission with T_{eff} in the 200,000 K – 1 million K range
- A data base with 23 objects with grating exposures, one outburst repeated (RS Oph) mostly with Chandra (some RGS, too).

Supersoft X-ray sources and non-ejecting novae

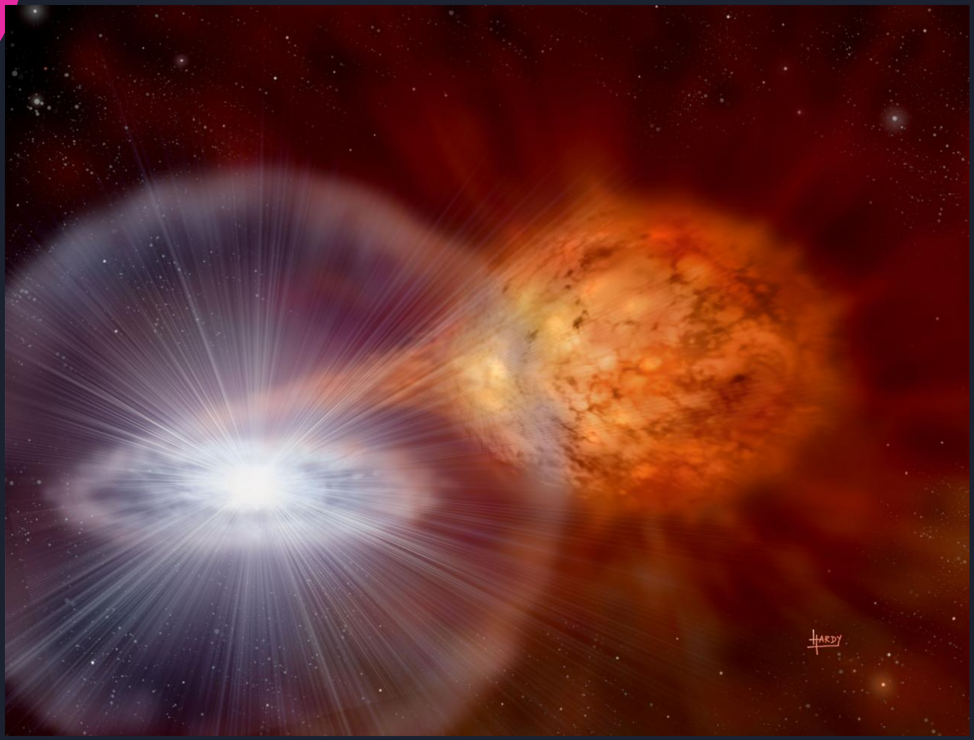
- A database of only 9 objects, mostly in the Magellanic Clouds
- The third phase may occur in objects that are never observed in a mass-ejecting nova outburst
- Three possibilities: high $\dot{m}$ with all energy irradiated immediately, persistent X-ray sources
- Periodic swelling with UV emission instead of X-rays
- Non-ejecting novae, a TNR occurs but no “superwind” follows
- In any case, high $\dot{m}$
- Recurrence time depending on $\dot{m}$ and m(WD), so persistent sources expected when they are high… but this is not always the case (SMC 13)

Novae as laboratories to study shocks



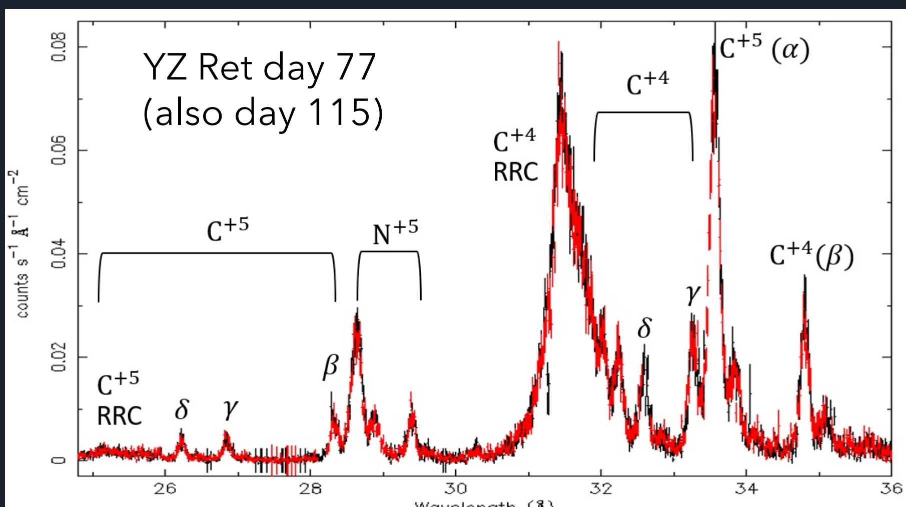
- : kT_{sh}~1.2 keV (v/1000 km)^2
- Initial shocks can occur with electron temperature ~30 keV
- But… often occur in a gas that is to dense to absorb hard X-rays but not too dense for the particle-particle loss time scale to be shorter than the particle acceleration time scale, because we do observe gamma-rays with Fermi even long before X-rays
- Rapid cooling with beautiful emission line spectra
- Not easy to analyse: more than one component, lack of equilibrium

The case of symbiotics



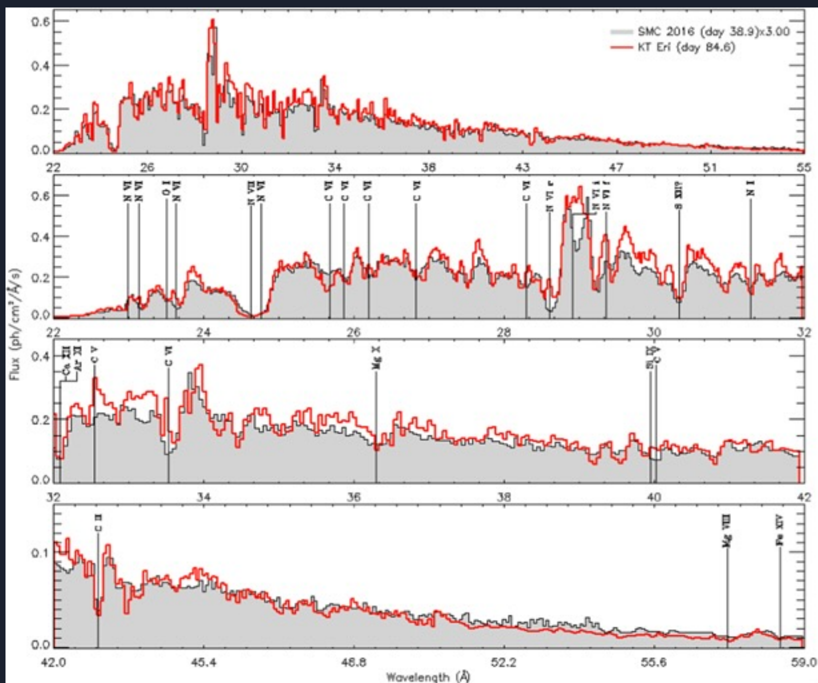
- Very rapid outbursts, most of our knowledge is from RS Oph at d~2.4 kpc
- V3890 Sgr and V745 Sco were also observed (2D calculations of Orlando and Drake)
- "Skewed" line profiles
- Much expected: T CrB at 800-900 pc
- CO or One WDs?

Early vs. late phase: the shocks continue



- Numerous cases of emission line spectra indicating shocks still occurring, in a cooler plasma, 2 months or more after the peak
- Emission line spectra observed also for some "persistent sources"
- Impossible to distinguish from "low end" of SSS without high resolution
- Case of YZ Ret, Mitrani et al. (2024):radiation recombination continua, evidence of charge exchange
- Line width interpreted as thermal broadening

The supersoft X-ray source in novae (I)

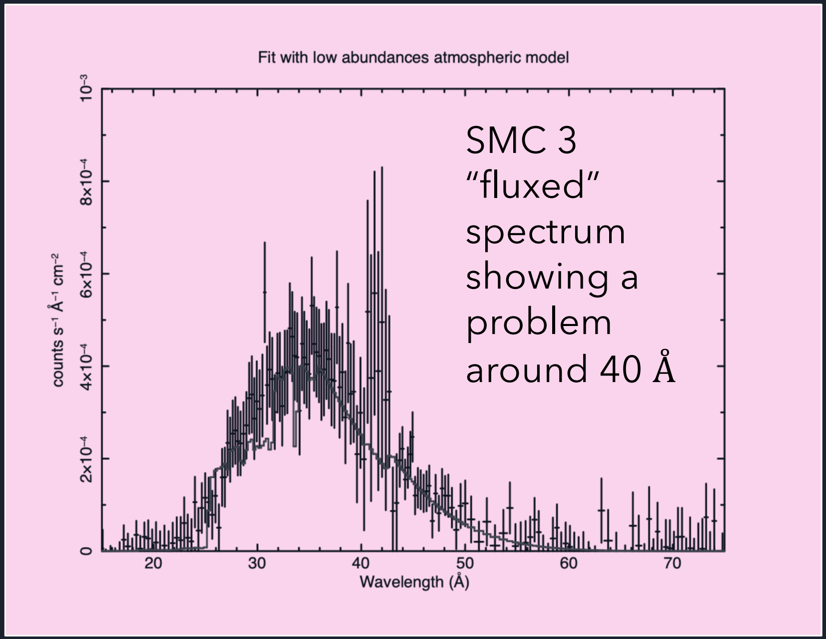


- While the ejecta thin out, the WD shrinks back to almost "regular" radius, the bolometric luminosity remains constant => shift to X-rays
- When mass loss is not detected in optical spectra and the burning is not extinguished, luminous SSS
- Many absorption lines, typical H-like and He-like elements, some gravitational broadening, but unexpected blue-shift indicating residual wind

The supersoft X-ray source in novae (II)

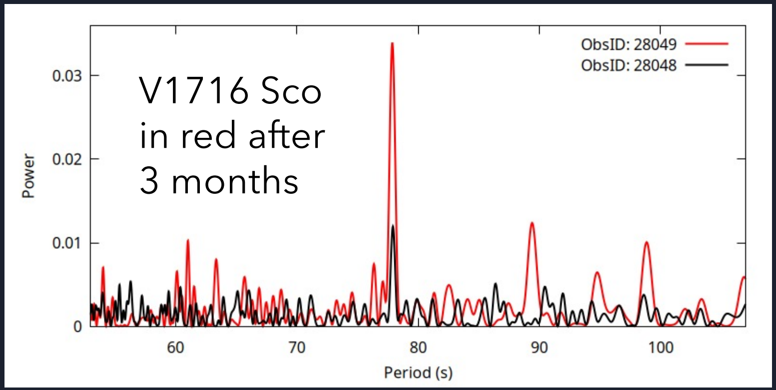
- Modelling these (NLTE) spectra is quite complex – the blue-shift complicates all
- But it is important: measuring T_{eff} allows to derive mass of WD! There is a direct relationship between the two.
- Some features also allow to distinguish between CO and ONe WDs.
- "Fit by comparison" with static models (Rauch et al. 2010) is very useful, but it is not realistically possible (yet) to build models for each set of abundances and m(WD)
- Using the SPEX PION model (photoionization producing absorption lines) produces also useful fits
- Other attempts: wind-type models (van Rossum 2013), LTE (Suleimanov et al. 2024 for static atmospheres)

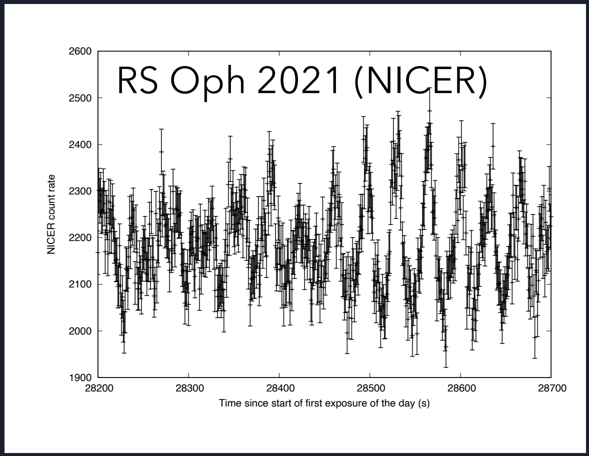
The "non ejecting" sources



- With $T_{eff} \leq 500{,}000$ K and $Lx \leq 10^{37}$ erg/s, even moderate absorption prevents obtaining "good" grating spectra
- They are still exceptionally useful to distinguish H-burning from emission lines spectra

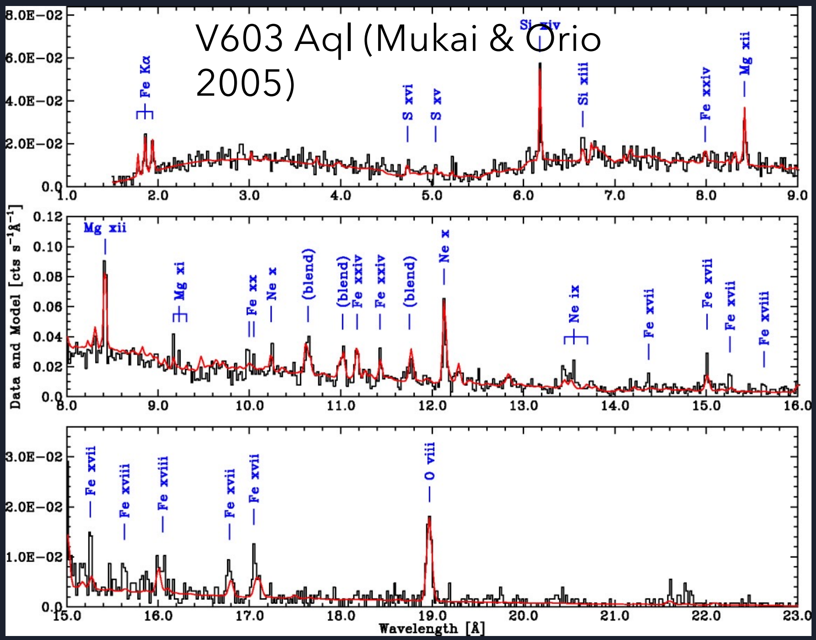
The mystery of the pulsations (QPOs?)





- The long exposures necessary for the gratings allowed to detect unexpected irregular variability (variable ionization stages in absorbing ejecta?)…
- … and regular variability
- ~10 min long pulsations revealed magnetic WDs in several novae
- The ~1 min pulsations well measured with Swift or NICER appear more stable in long Chandra exposures => clue to stellar pulsations or rotation?

The quiescent accreting sources



- Novae are luminous and rare, so for a selection effect they are discovered at a few kpc or… in external galaxies
- Few examples of grating spectra, precious to understand accretion
- CCD-type instruments also very useful, especially for timing