Nova shells lecture

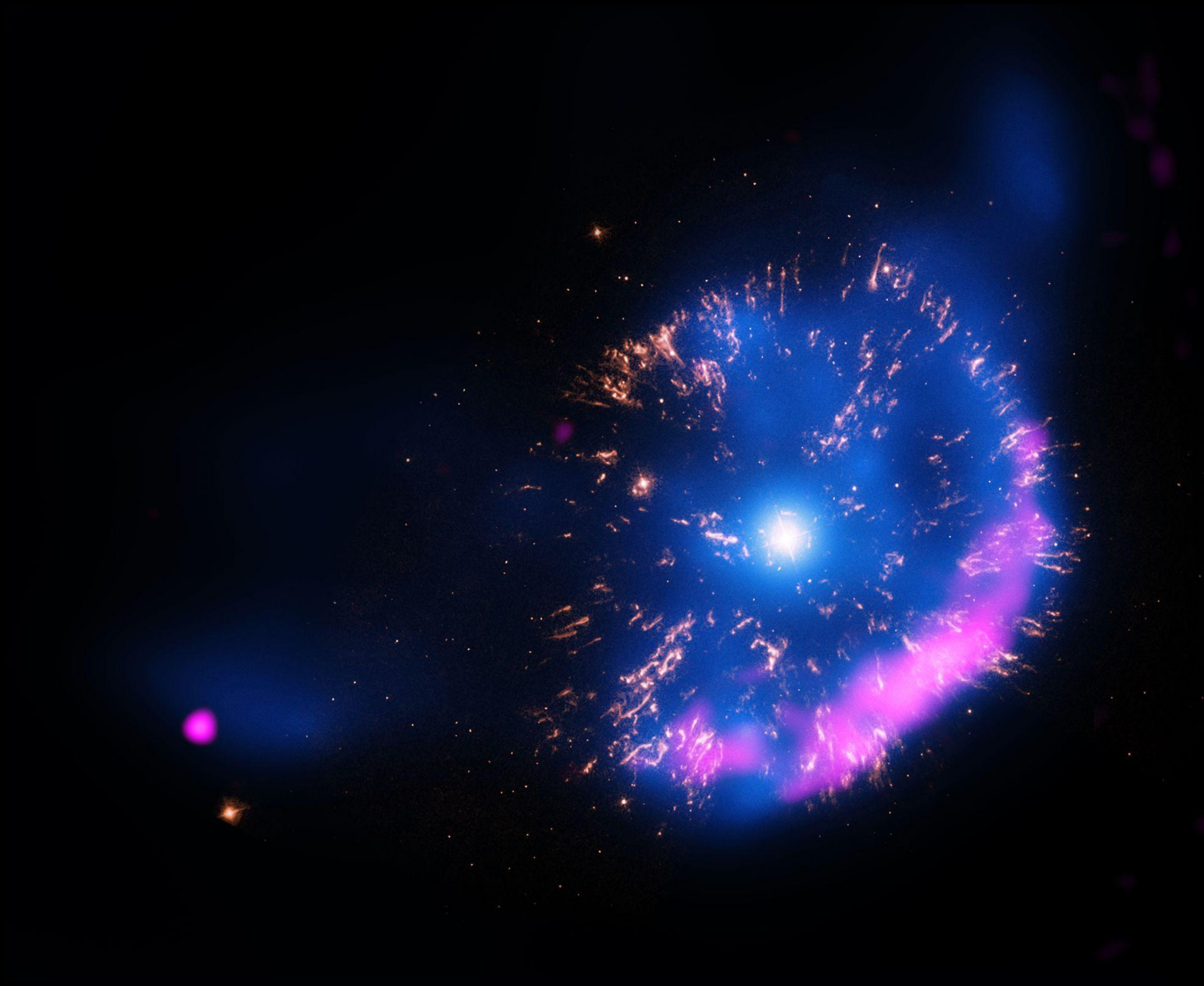
Instituto de Física y Astronomía

Universidad de Valparaíso CHILE

GK Per, credits: NASA

Close Binary Stars
Lientur Celedón
9th of October, 2025

Ha
VLA
Chandra

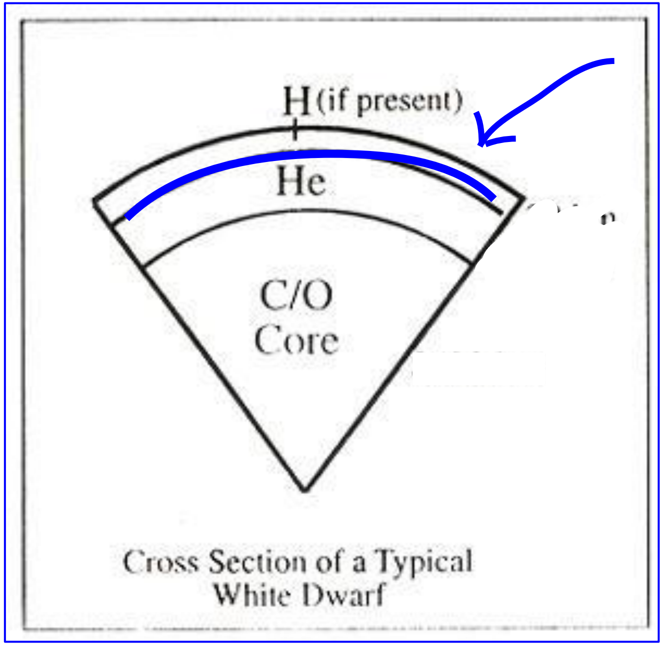


GK Per,
Nova Per 1901,
Takei et al, 2015

Thermonuclear runaways (TNRs)

Brief summary of

Thermonuclear Run Away (TNR)



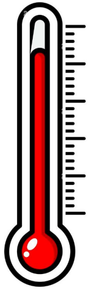
Sketch of WD structure

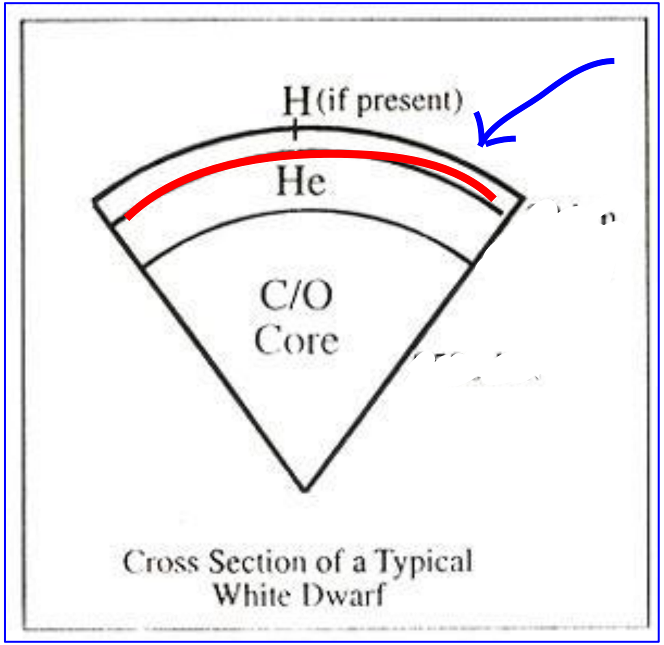
- Hydrogen is accumulated over the surface forming a layer which bottom is electron degenerate.

Starrfield et al, 2016
Jose 2016

Brief summary of

Thermonuclear Run Away (TNR)





Sketch of WD structure

- Hydrogen is accumulated over the surface forming a layer which bottom is electron degenerate.
- Conditions for a TNR are reached before reaching the Fermi temperature (~10^7 K).

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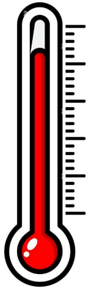
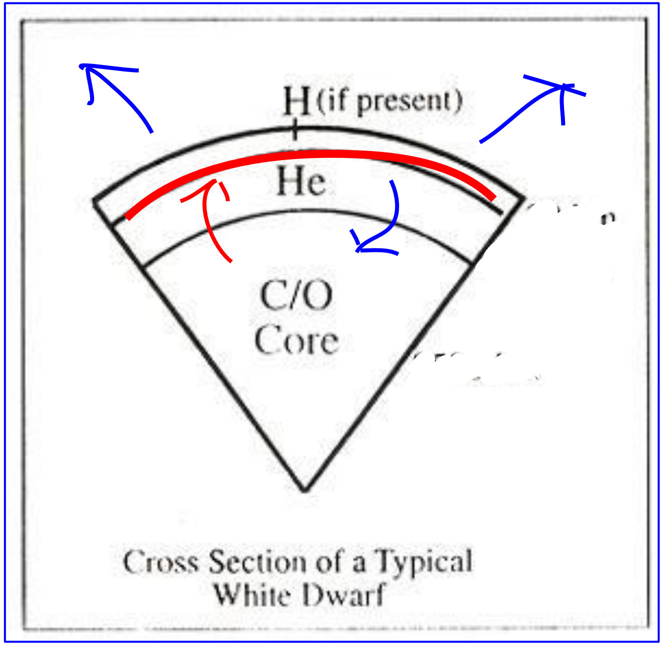
Brief summary of

Thermonuclear Run Away (TNR)





Sketch of WD structure

- Hydrogen is accumulated over the surface forming a layer which bottom is electron degenerate.
- Conditions for a TNR are reached before reaching the Fermi temperature (~10^7 K).
- H fuses into He through p-p chain, and hot CNO cycle.
- Kelvin-Helmholtz instabilities drag material from the WD core.

Starrfield et al, 2016
Jose 2016

Brief summary of

Thermonuclear Run Away (TNR)

The amount of H required for a TNR depends on the WD mass:

$$P_{\rm crit} = \frac{G M_{\rm WD} M_{\rm envl}}{4\pi R_{\rm WD}^4},$$

$$M_{\rm envl} \propto \frac{R_{\rm WD}^4}{M_{\rm WD}},$$

$$R_{\rm WD} \propto M_{\rm WD}^{-1/3},$$

Starrfield et al, 2016
Jose 2016

Brief summary of

Thermonuclear Run Away (TNR)

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$$M_{\rm envl} \propto \frac{R_{\rm WD}^4}{M_{\rm WD}},$$

$$R_{\rm WD} \propto M_{\rm WD}^{-1/3},$$

$$M_{\rm envl} \propto M_{\rm WD}^{-7/3}.$$

More massive WD requires less accreted mass to produce a TNR.

Starrfield et al, 2016
Jose 2016

Brief summary of

Thermonuclear Run Away (TNR)

Because they have a lower level of degeneracy, low mass WD produces less energy during the TNR.

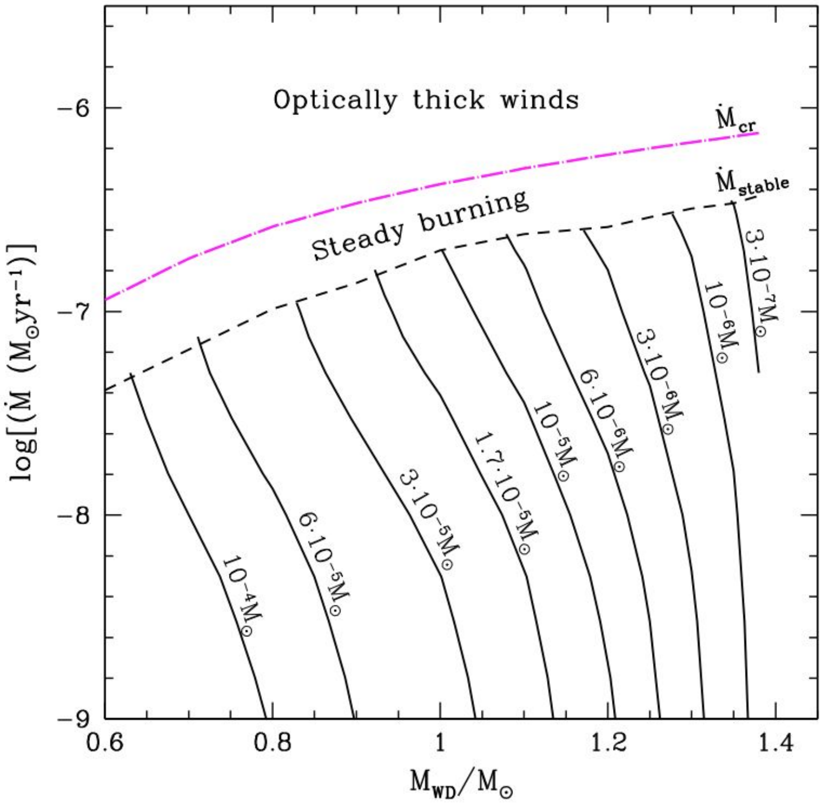
More massive WD have higher escape velocities.

The velocity of the ejecta is higher for more massive WDs.

Starrfield et al, 2016
Jose 2016

Thermonuclear Run Away (TNR)

M_{env} depends on M_{WD}, $\dot{M}$, and on a minor level on chemical composition.

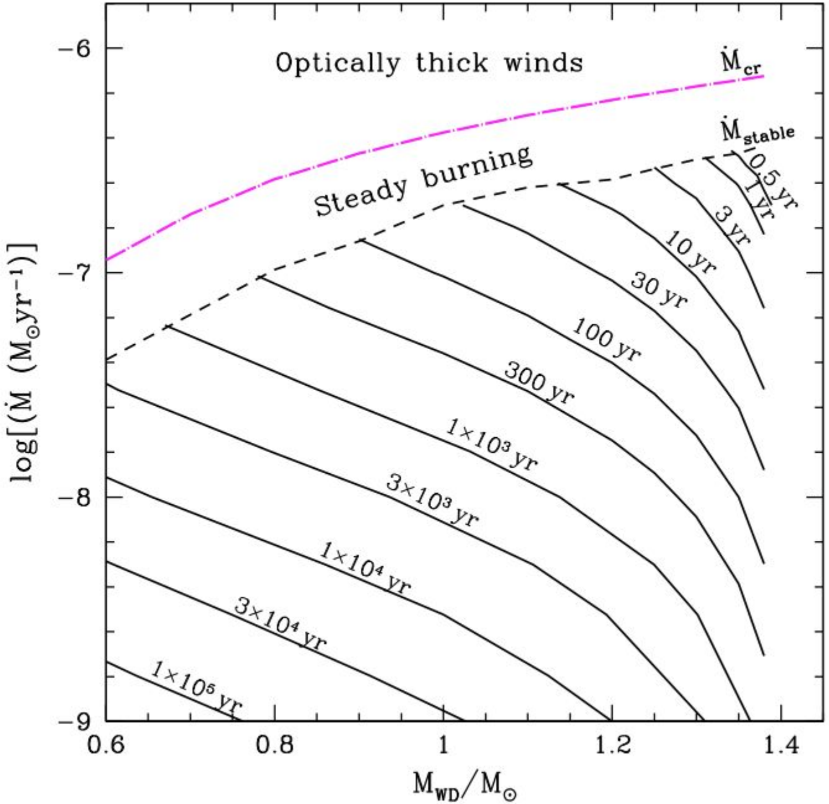


Kato et al, 2014

Brief summary of

Thermonuclear Run Away (TNR)

Recurrence times between TNR varies, spanning a range between years and millennials.

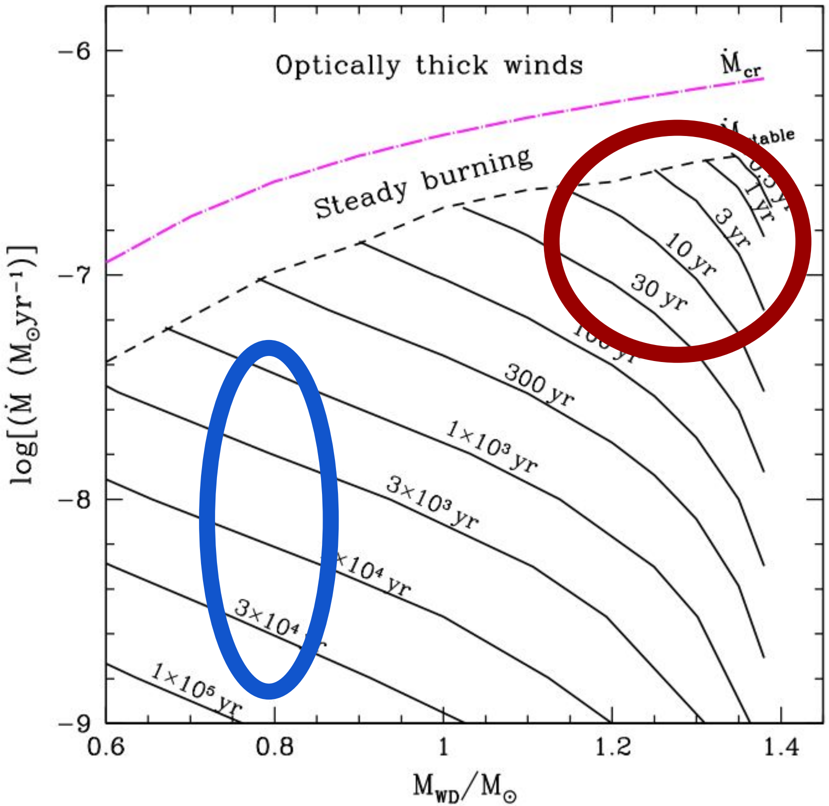


Kato et al, 2014

Brief summary of

Thermonuclear Run Away (TNR)

Recurrence times between TNR varies spanning a range between years and millennials.



Recurrent Novae:
Lower recurrence times
Lower accreted masses
Less massive, faster ejecta

Classical Novae:
Higher recurrence time
Higher accreted masses
Higher mass, slower ejecta

Kato et al, 2014

Brief summary of

Thermonuclear Run Away (TNR)

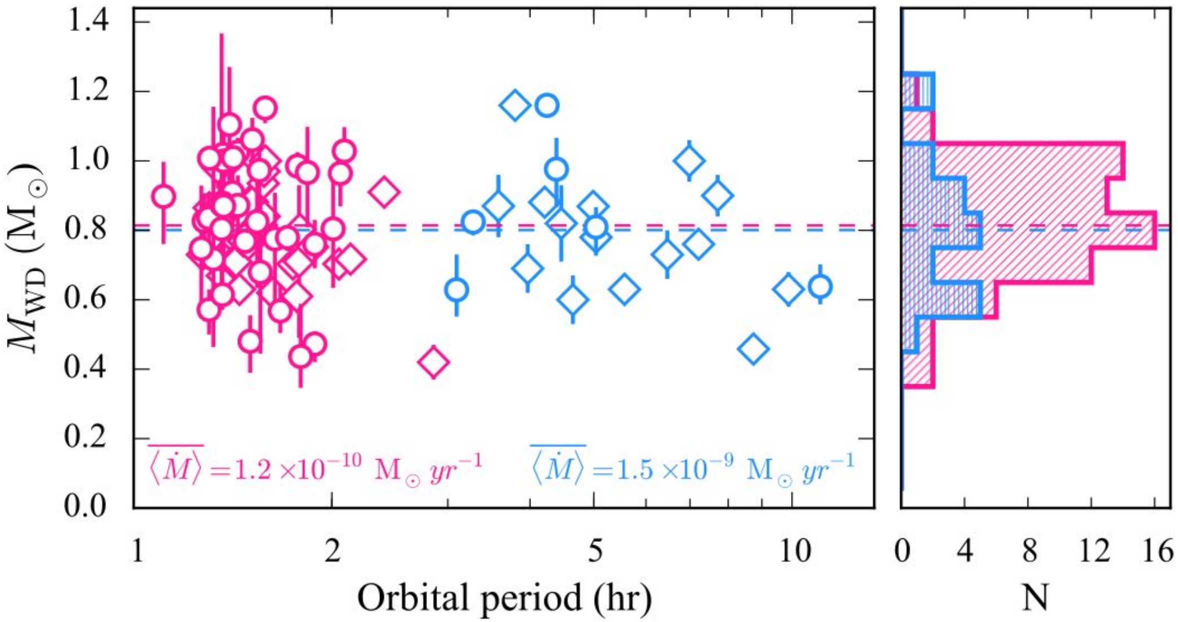
Does the WD gain mass after a TNR?

Thermonuclear Run Away (TNR)

Does the WD gain mass after a TNR?

Evolved CVs (lower periods) does not show systematic higher masses than younger CVs (higher periods).

All the accreted mass is ejected



Pala et al, 2022

Brief summary of

Thermonuclear Run Away (TNR)

To summarise..

- The accreted mass required to trigger a TNR is inversely proportional to the WD mass.
- More massive WDs produce faster ejecta.
- Recurrence time depends mostly on the WD mass and the accretion rate.
- All the accreted mass is ejected during the TNR.

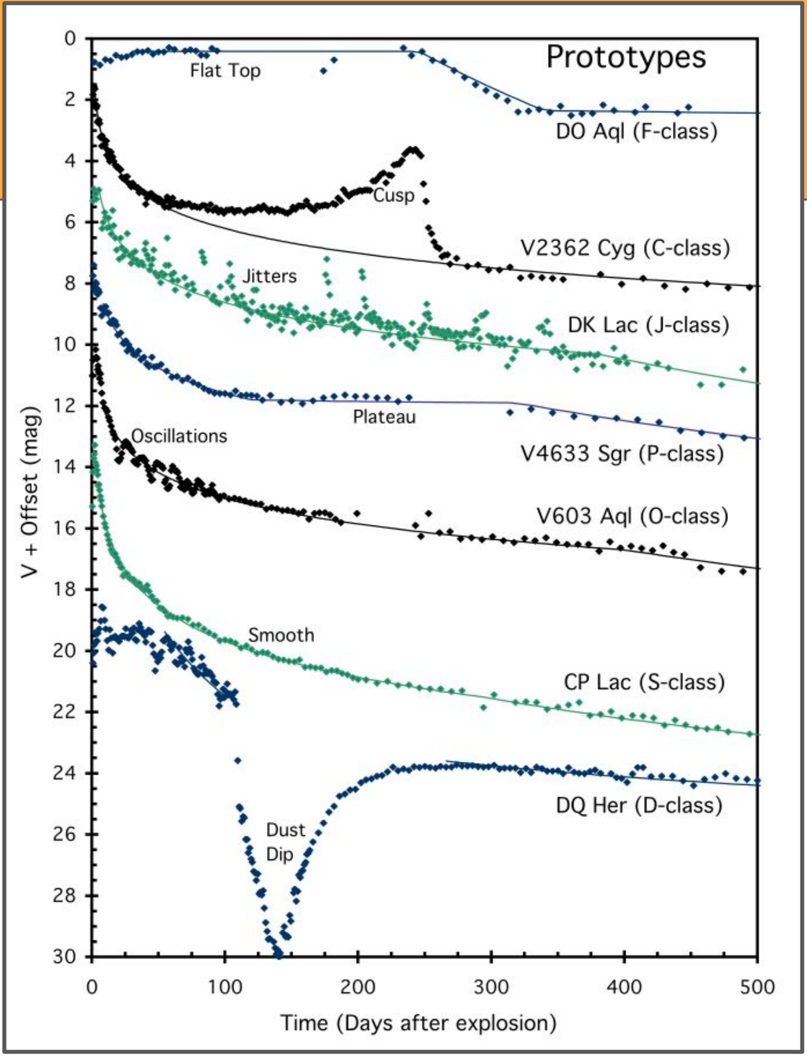
Nova eruptions

Novae are complex

A nova eruption is a process that could last hundred of days.

Their diversity is revealed by the morphology of their light curves.

There is no current consensus on what causes this diversity.



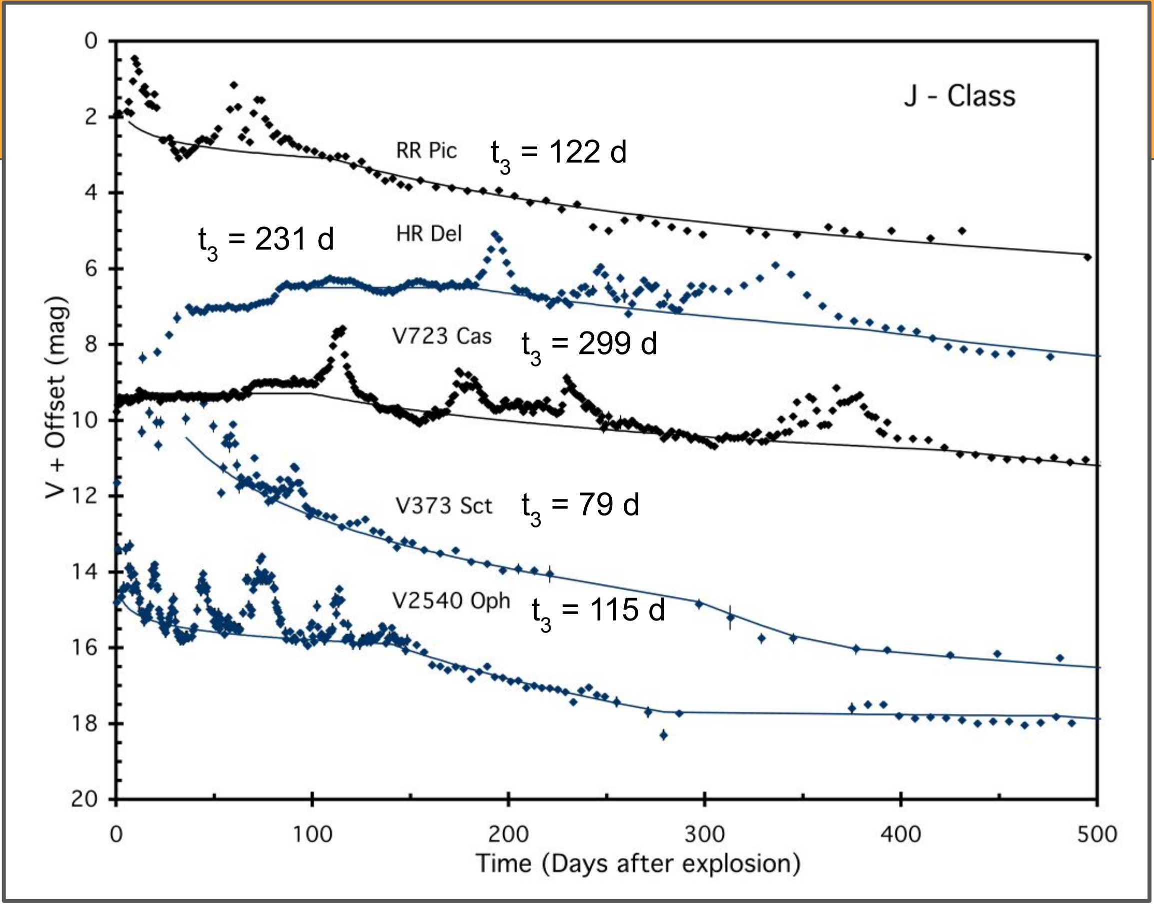
Strope et al, 2010

Novae are complex

A nova eruption is a process that could last hundred of days.

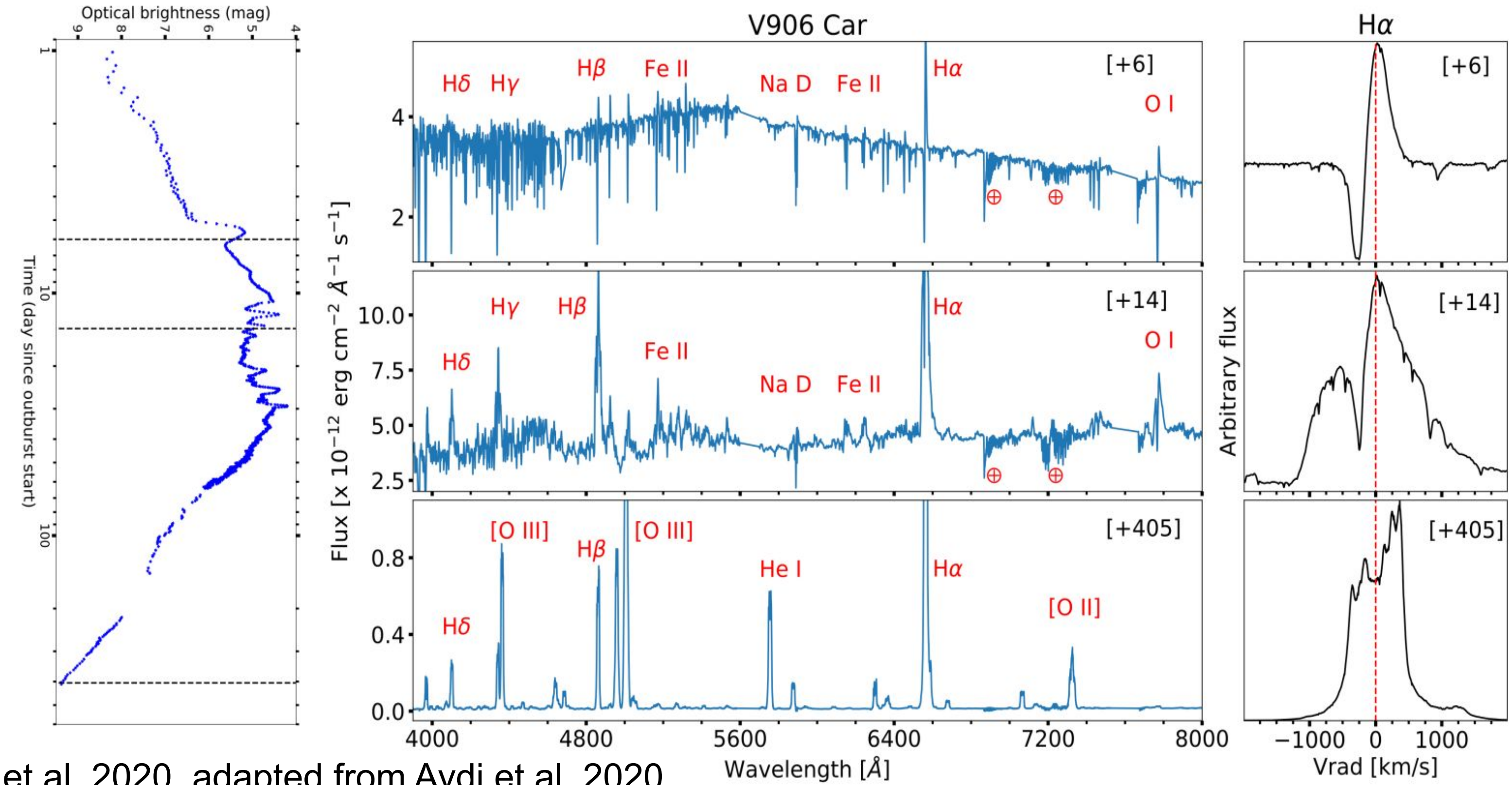
The speed at which the nova evolves also varies.

t_3 = time required for the light curve to drop 3 mag after its maximum brightness.



Strope et al, 2010

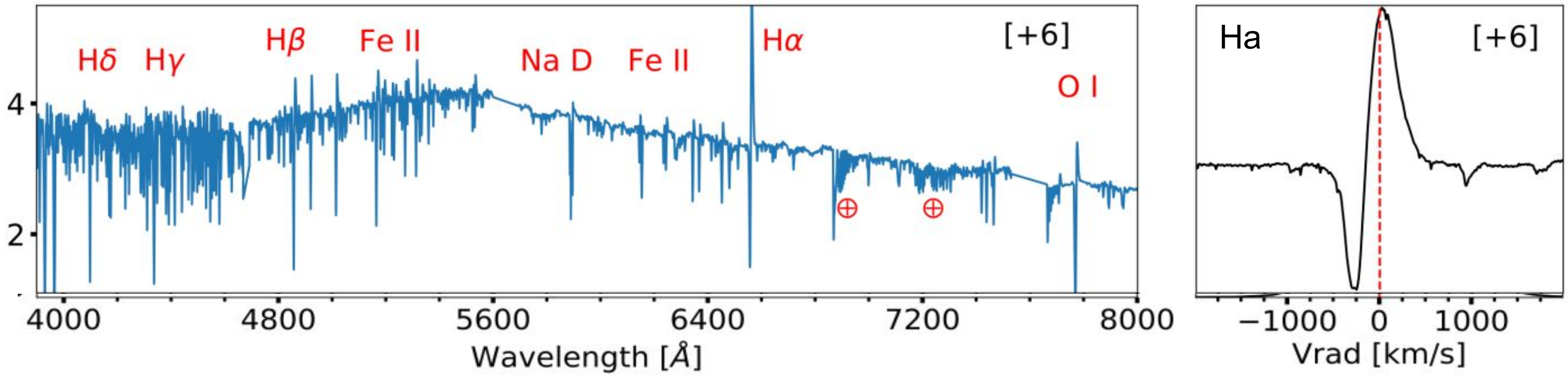
First days after Nova : V906 Car (Nova Carinae 2018)



Chomiuk et al, 2020, adapted from Aydi et al, 2020

First days after Nova : V906 Car (Nova Carinae 2018)

6 days after eruption : Photospheric phase

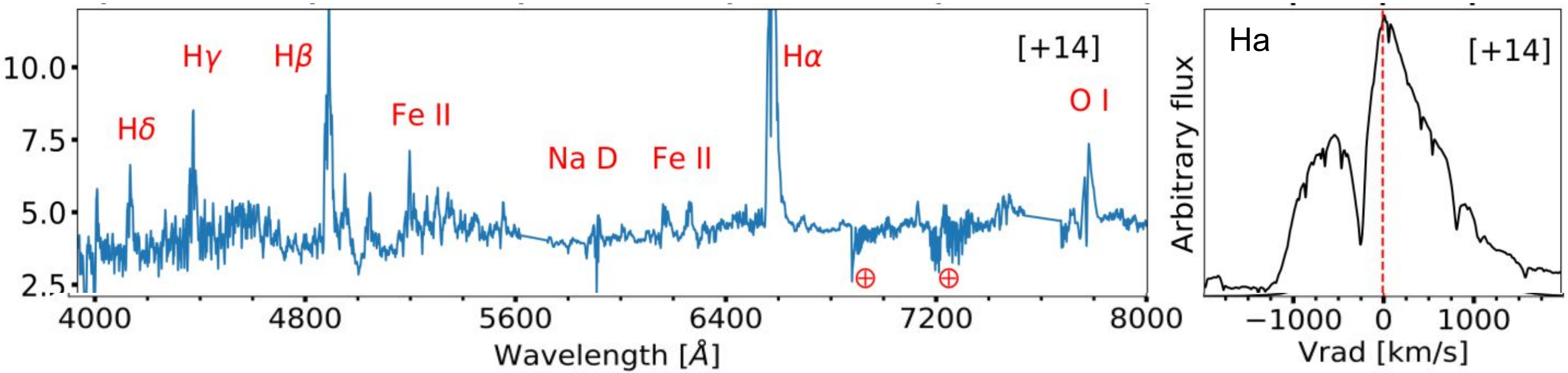


- As the thick ejecta leaves the system, the spectrum is dominated by absorption lines.
- The P-Cygni profile indicates expansion velocities of ~500 km/s.

Chomiuk et al, 2020, adapted from Aydi et al, 2020

First days after Nova : V906 Car (Nova Carinae 2018)

14 days after eruption : Transition phase

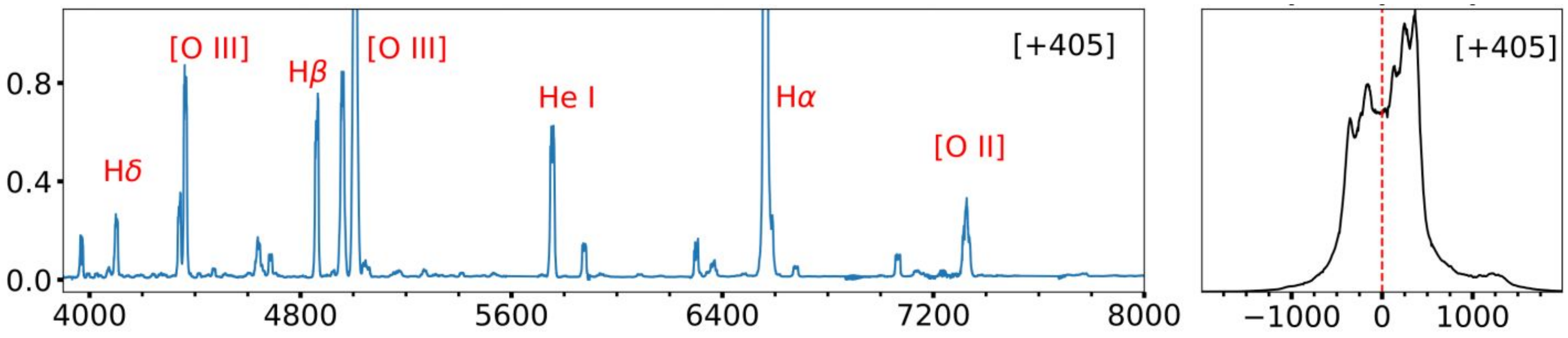


- As the ejecta expands it starts to transitioning from a thick to a thin medium. Ionized and forbidden emission lines start to appear.
- A fast (~1000 km/s) component starts to dominate the spectrum.

Chomiuk+20, adapted from Aydi+20

First days after Nova : V906 Car (Nova Carinae 2018)

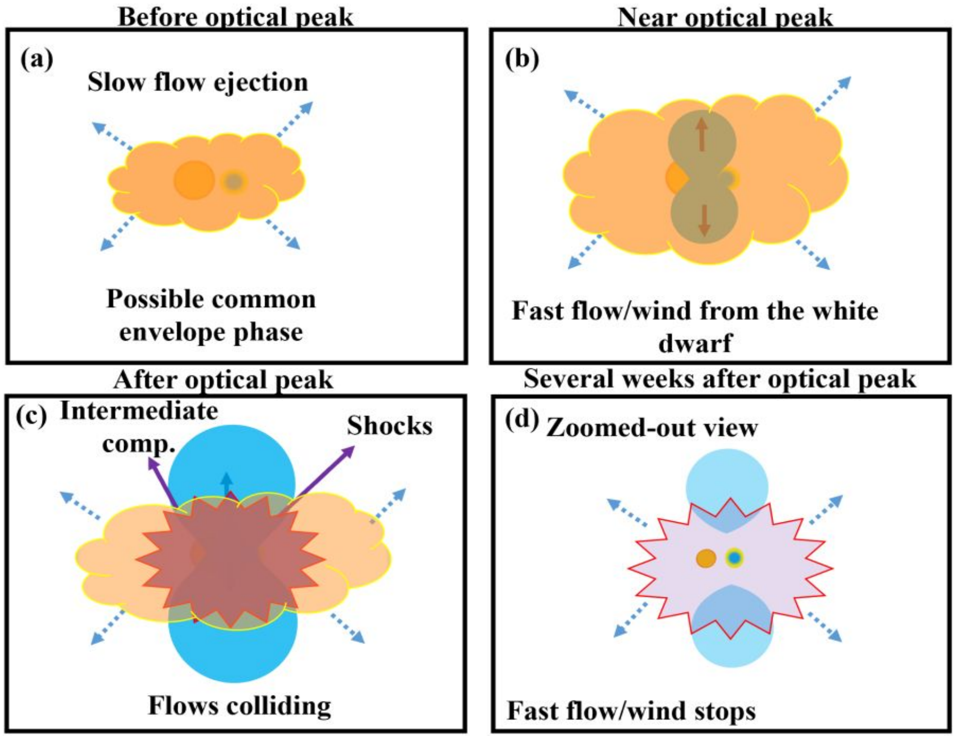
405 days after eruption : Nebular phase



- The spectrum is full dominated by emission (allowed and forbidden) lines.
- The castellated profile reveals clumpines and non-spherical geometries.

Chomiuk+20, adapted from Aydi+20

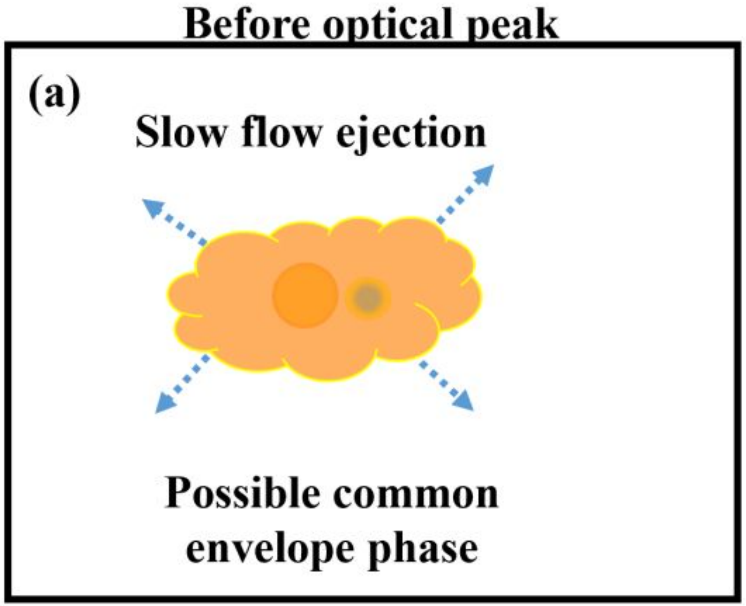
A proposed universal model for nova eruptions



Aydi et al, 2020

- Aydi et al, 2020 proposed an universal mechanism for nova eruptions.
- At least two distinct outflows, one slow, equatorial, followed by a faster, polar outflow.
- The interaction between flows is the main source of brightness observed in novae.

A proposed universal model for nova eruptions



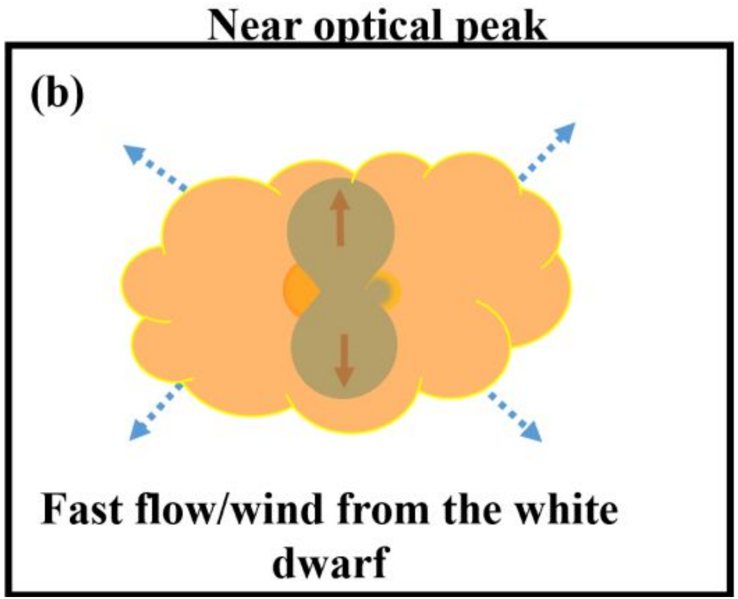
The accreted enveloped is puff up due to the energy of TNR.

A short Common Envelope phase is produced (possible extra source of angular momentum loss).

Most of the ejected mass is confined in this slow ejecta (Shen & Quataert 2022)

Aydi et al, 2020

A proposed universal model for nova eruptions

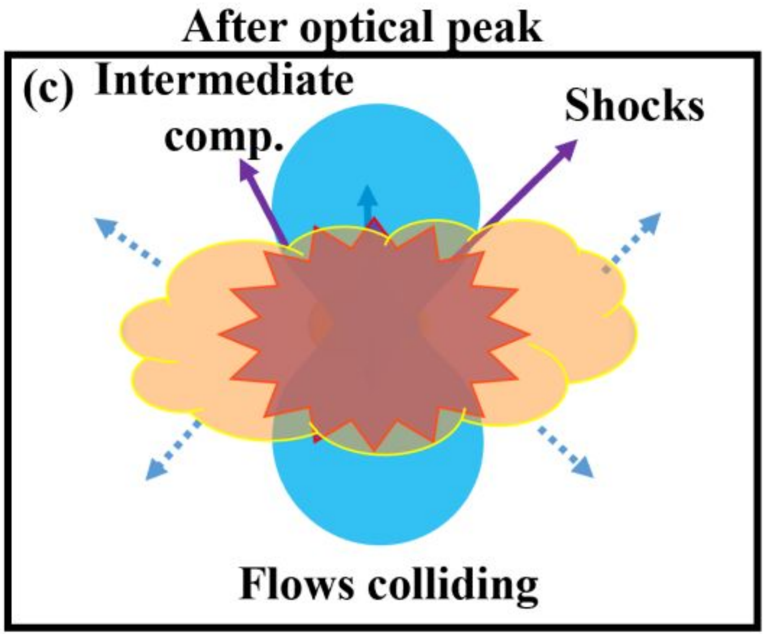


A fast wind originates from the WD due to the radiation of the ongoing burning.

Propagation on polar directions is easier as less material is present.

Aydi et al, 2020

A proposed universal model for nova eruptions

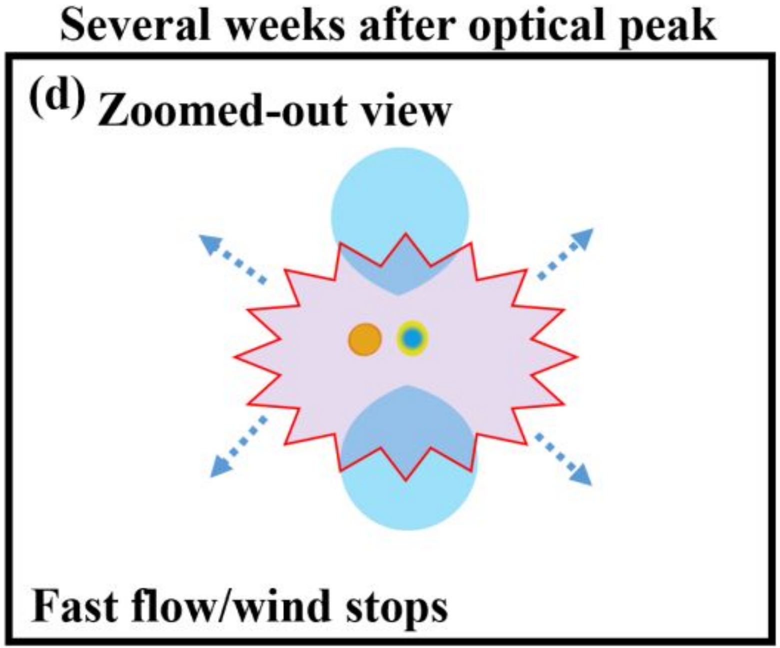


Eventually the fast wind catches the slow one. The interaction between components produces shocks and accelerates the slow one.

The energy released during the shockspower a substantial fraction of the nova luminosity.

Aydi et al, 2020

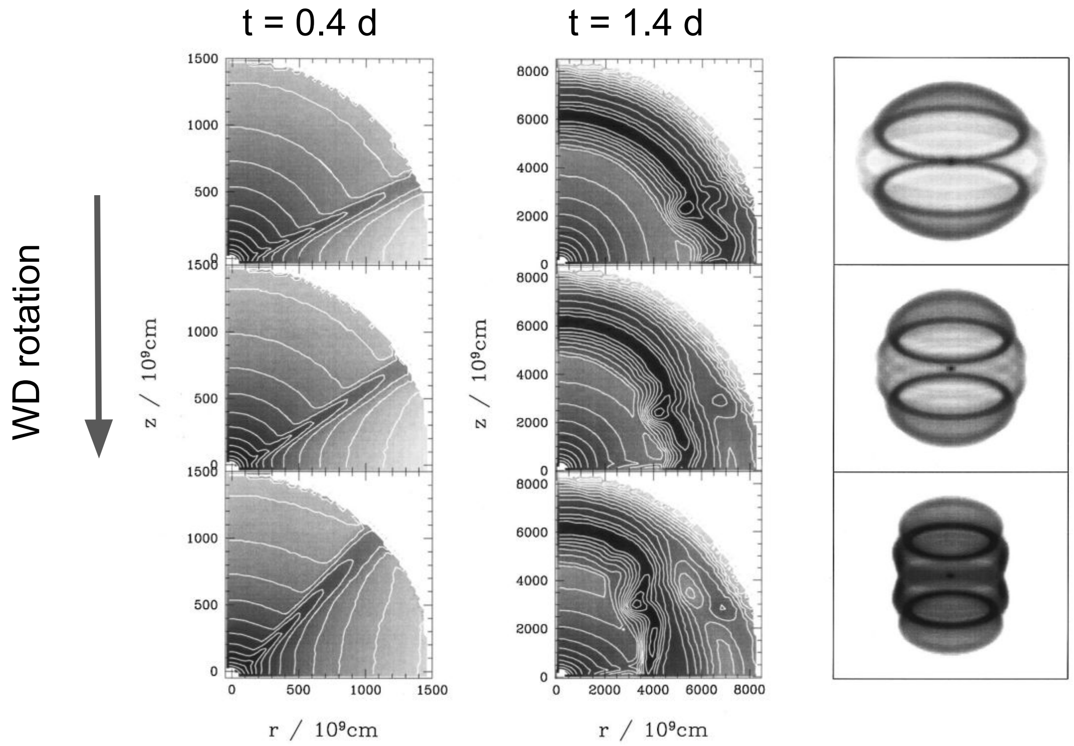
A proposed universal model for nova eruptions



The fast wind stops and the ejecta is “freeze” as it expands.

Aydi et al, 2020

Hydrodynamic simulations

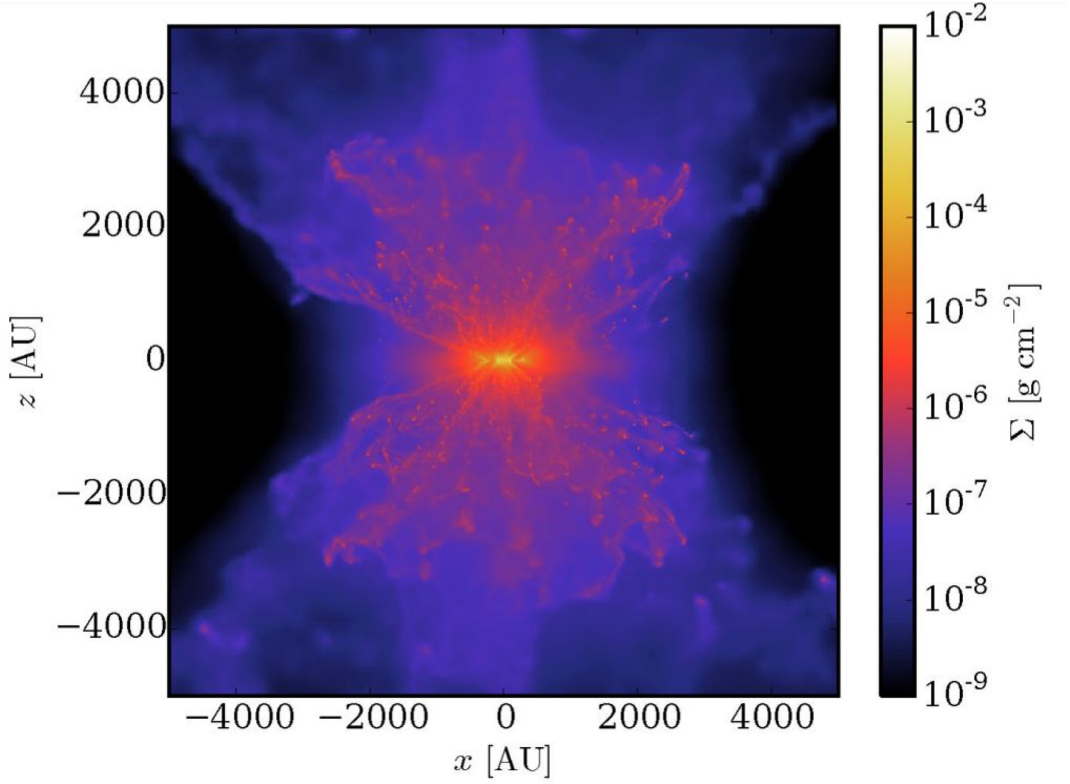


Hydrodynamic simulations predict prolate shapes.

WD rotation could play a significant role in the shape of the ejecta.

Porter et al, 1998

Hydrodynamic simulations



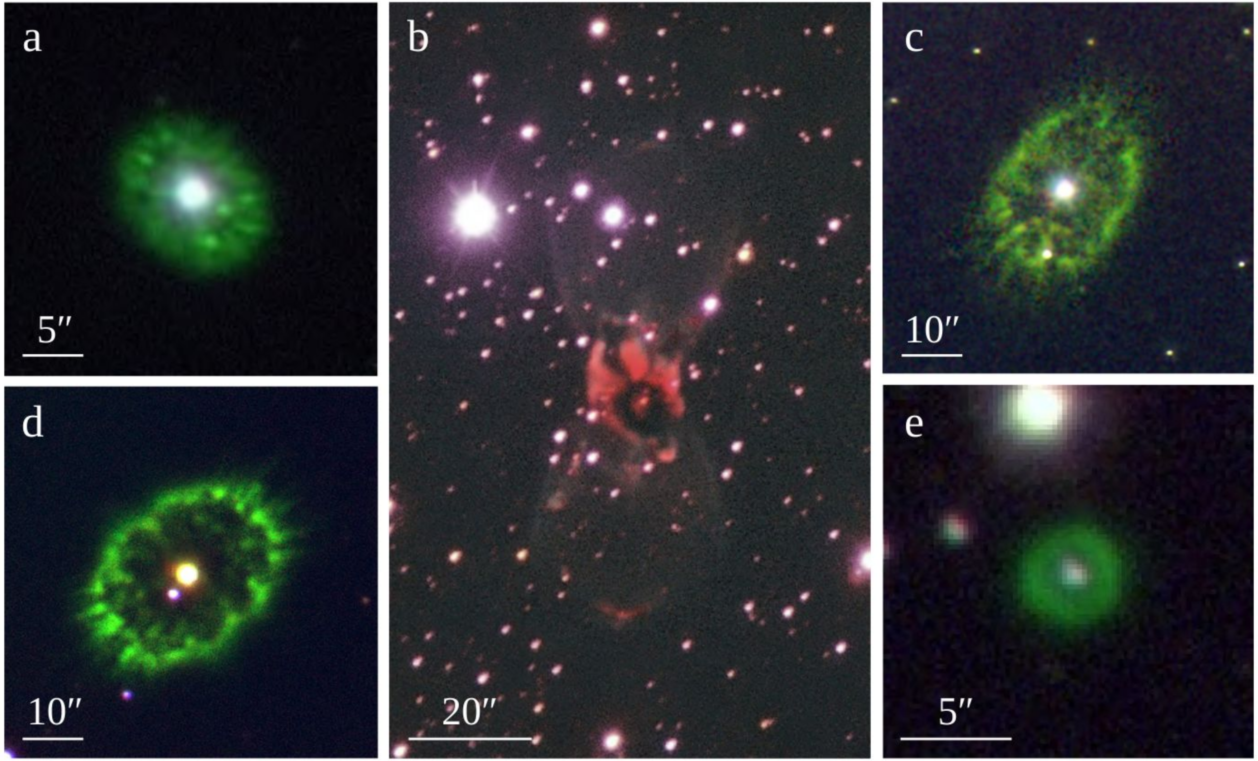
Hydrodynamic simulations predict prolate shapes.

Clumpy structures appear as the material expands and colds.

RS Oph,
Booth et al, 2016

Nova shells

Narrow band images



Santamaria et al, 2022

a) HR Del (~53 yrs old)
b) CK Vul (~348 yrs old[1])
c) T Aur (~125 yrs old)
d) DQ Her (~84 yrs old)
e) QU Vul (~36 yrs old)

Nova shells are observable in Hα+[NII] decades after the nova eruption.

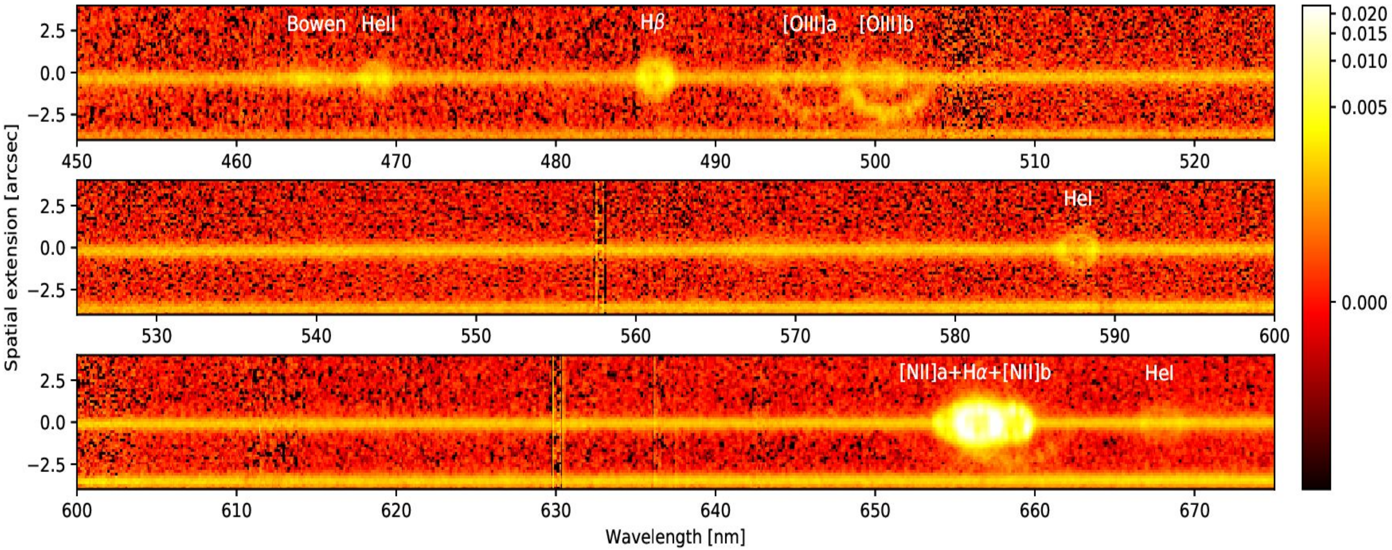
Sometimes in Hβ, [OIII] or HeI

[1]D. P. K. Banerjee+20

Long slit spectroscopy

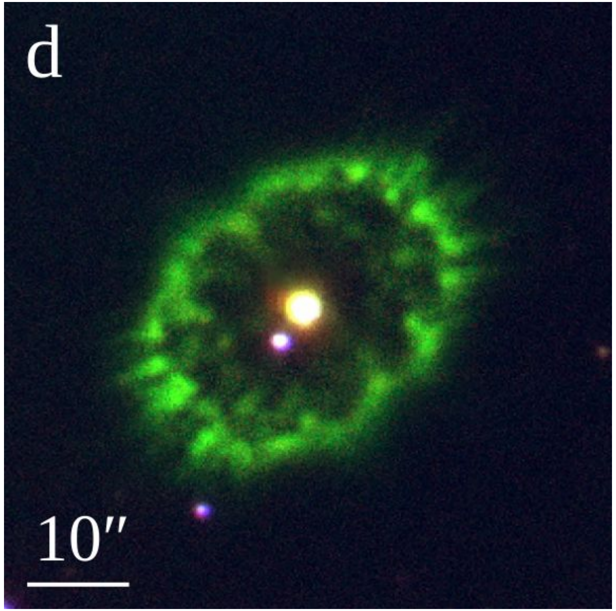
V1425 Aql

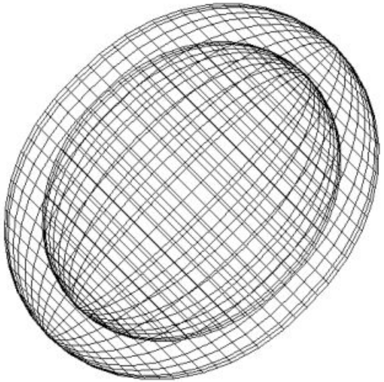
Long slit spectroscopy can reveal spatial and kinematic information about the nova shell.



Tappert et al, 2023

Nova shells geometry





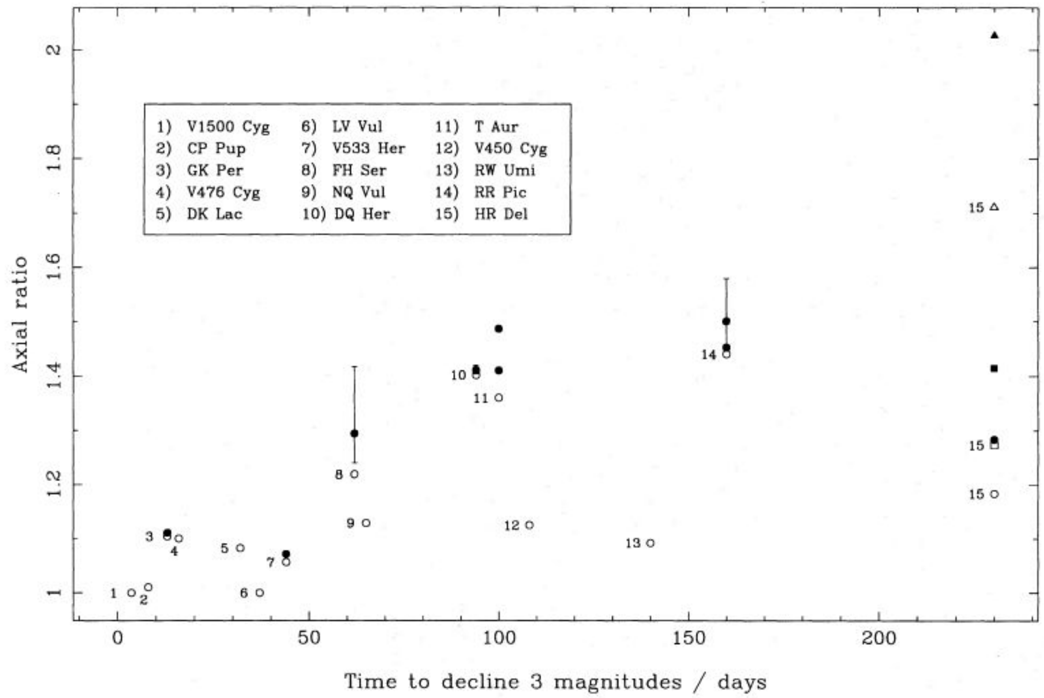
Model for the shell around DQ Her using the SHAPE software (Santamaria et al, 2022)

By combining the information from images and long slit spectra it is possible to reconstruct the geometry of the nova shell.

Prolate spheroids are the usual geometry.

Fastest novae shows more spherical shells.

Nova shells geometry



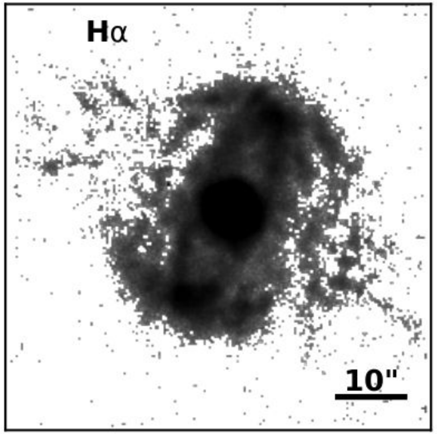
Axial ratio of nova shells correlates with their t3 parameter
Slavin et al., 1995

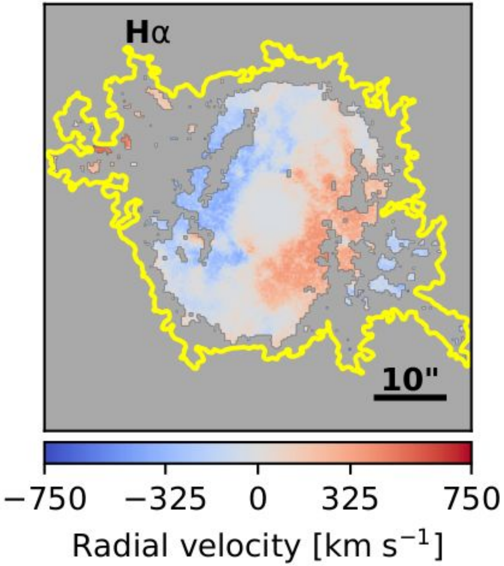
Observations show that faster nova eruptions produce more spherical and clumpier shells.

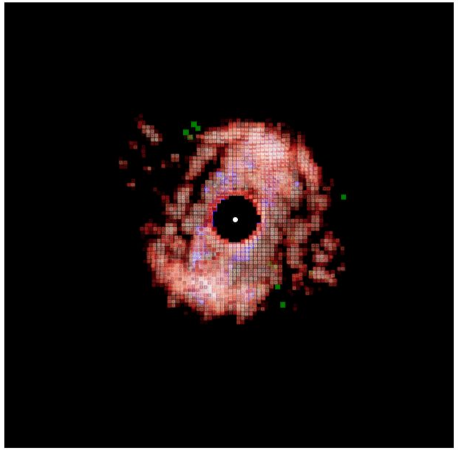
The reason behind is thought to be in the interaction between the ejecta and the secondary.

Nova shells geometry

Integral field spectroscopy provides a 3D view of the shell



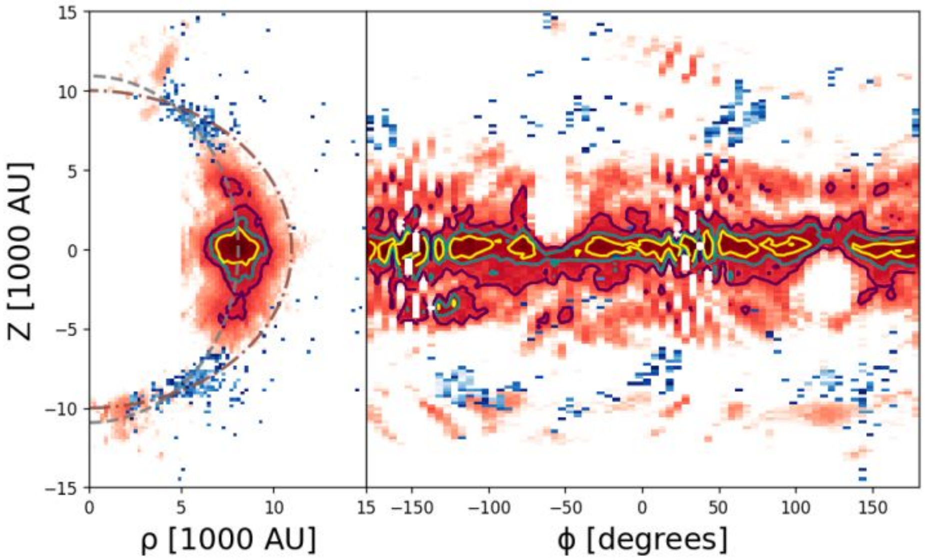




RR Pic nova shell
Celedón et al, 2024

Nova shells geometry

Integral field spectroscopy provides a 3D view of the shell

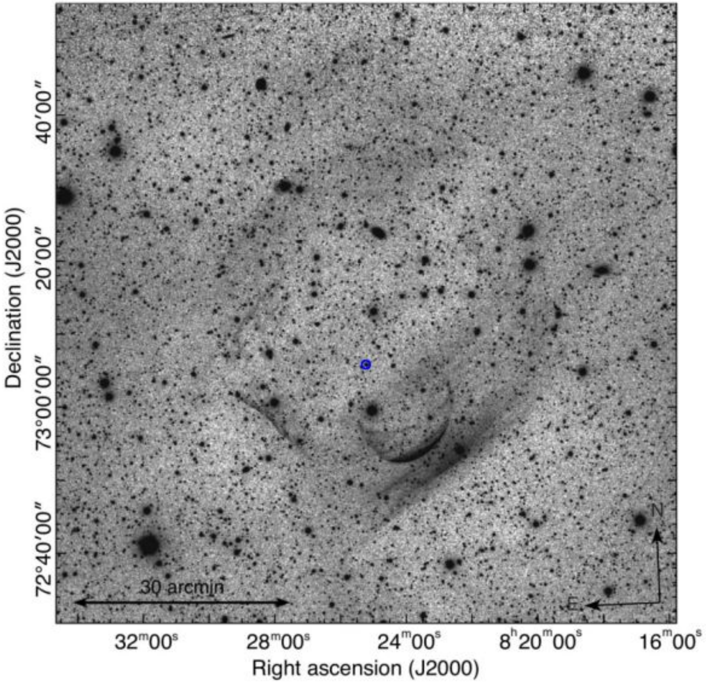


RR Pic nova shell
Celedón et al, 2024

Allow us to study the geometry of the shell from different perspectives, as well as the spatial differences between different emissions.

[OIII] originates in the gaps between the equatorial ring and polar filaments in Ha.

Ancient shells and nova super-remnants



Z Cam Hα+[NII] image (Shara et al, 2024)

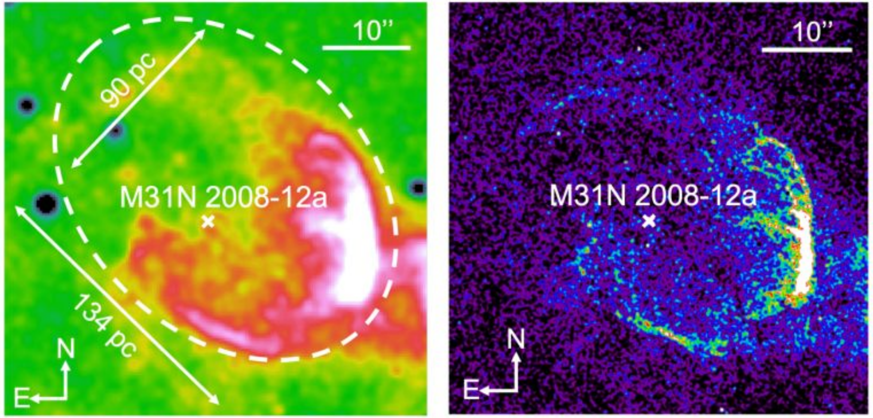
The oldest* nova shell is Z Cam. Possible remnant of ancient nova registered by chinese astronomers in 77 BCE.

A ~dozen of ancient shells have been discovered, with ages ~centuries old.

They could give us hints on the effect of nova in the CV centuries after the eruption.

*recent ancient shells discoveries around KT Eri and U Gem could be older

Ancient shells and nova super-remnants

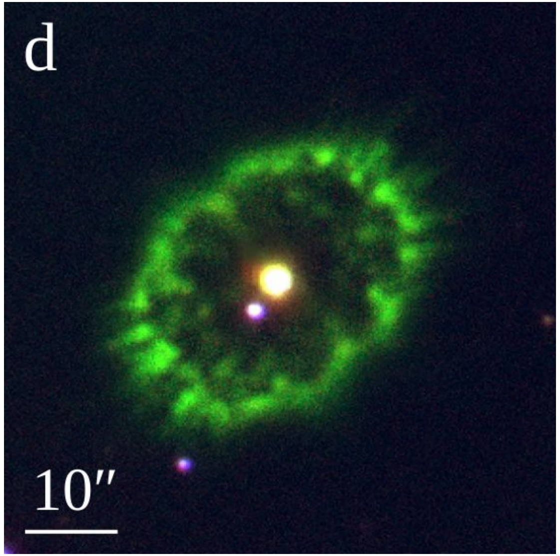


Nova super-remant around 12a, a RNe in M31 with a recurrence time of ~1 year (Darnley et al., 2019).

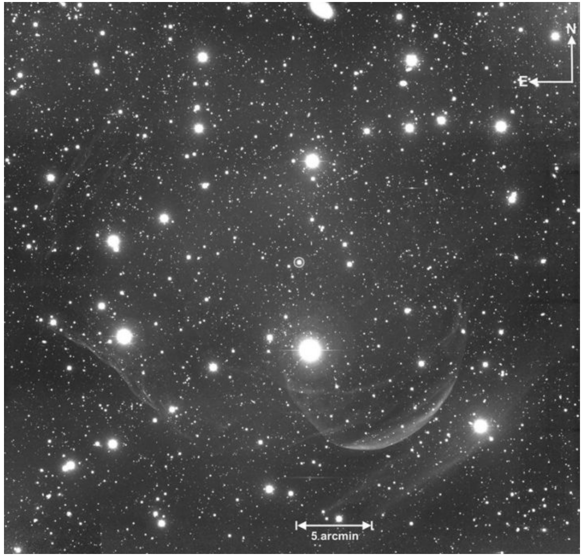
On recent years a new class of shell, orders of magnitude larger has started to been discovered around RNe.

Five NSR has been discovered:KT Eri, RS Oph, T Crb, M31 12a, and LMC 08a. (Healy-Kalesh et al., 2025)

Nova shell evolution



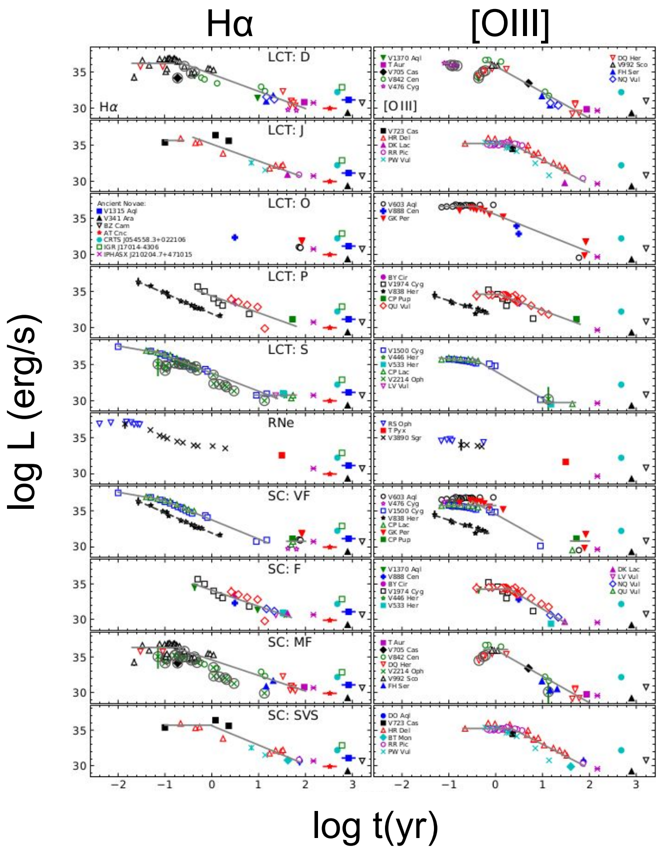
?



~84 years old

~2000 years old

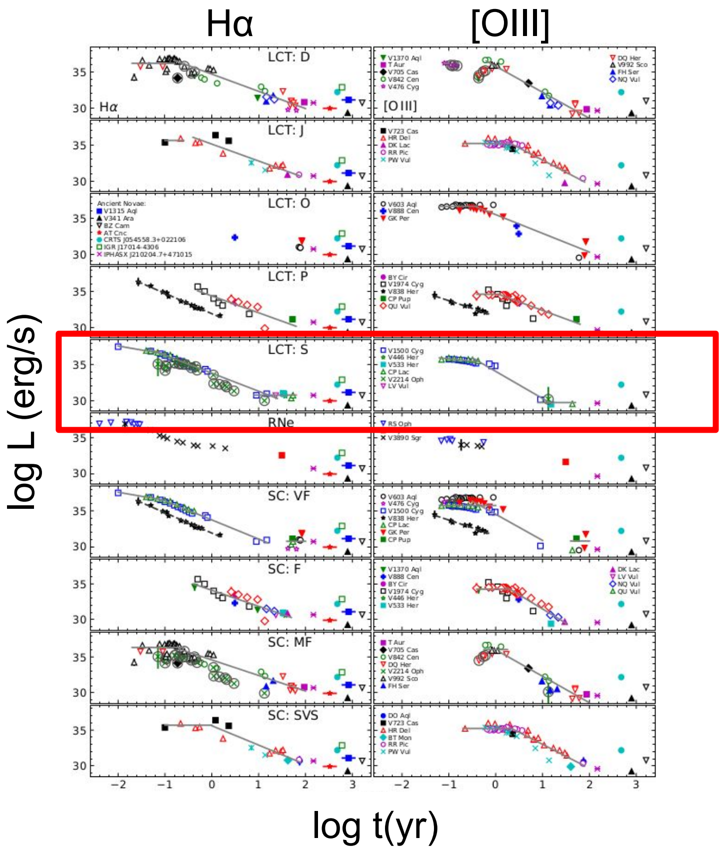
Luminosity evolution



The evolution of nova shells luminosity (Hα and [OIII]) with time was explored by Downes et al, 2001 and Tappert et al, 2020.

Data was grouped by light curve type and speed class

Luminosity evolution



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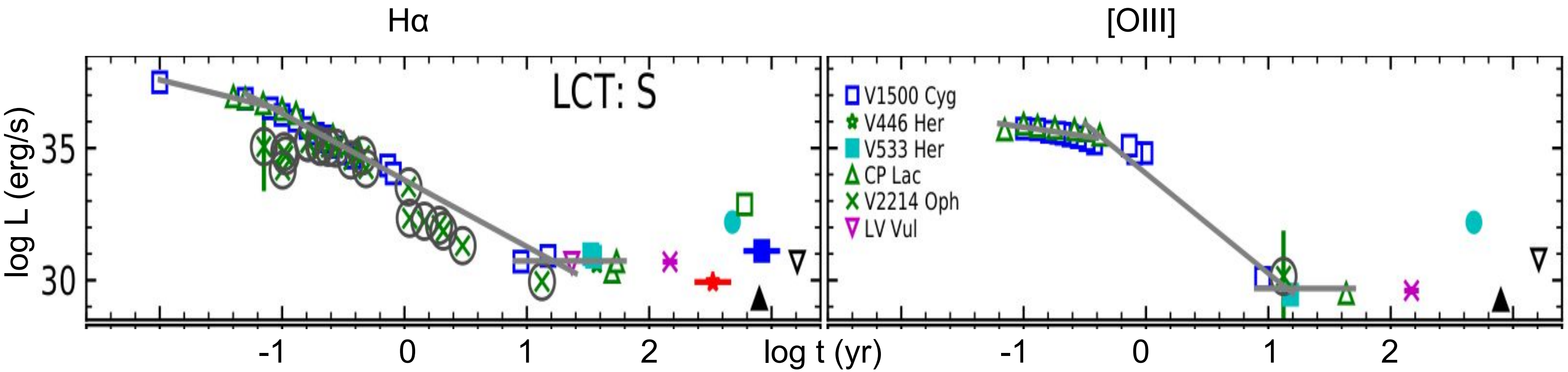
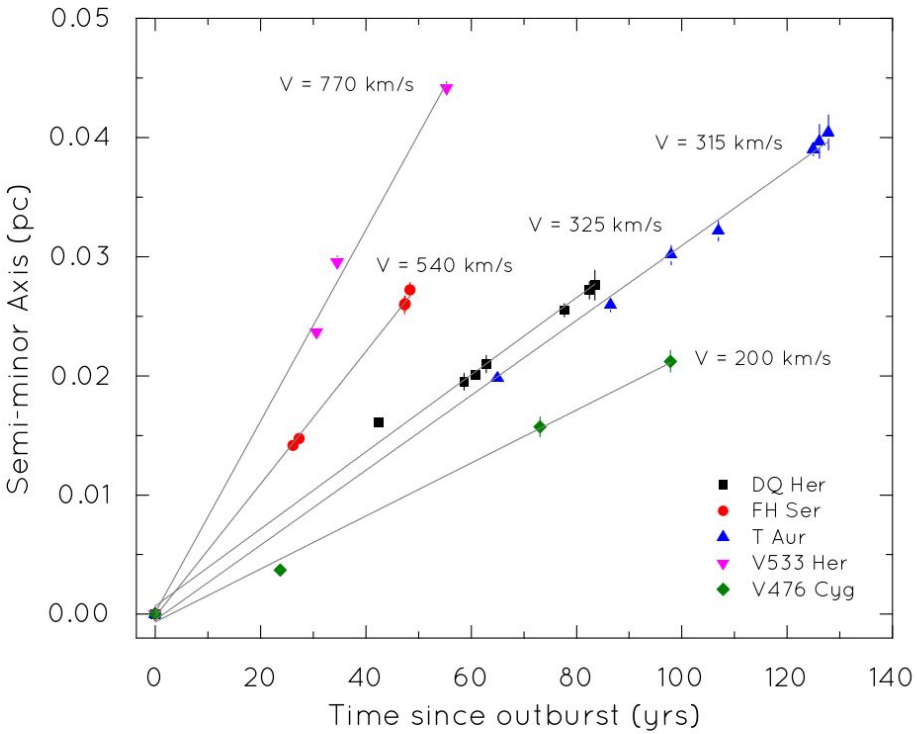
Luminosity evolution



The overall behaviour is represented by 3 stages: a smooth decline, a steep decline and a tentative plateau:

- smooth decline : the shell becomes optically thin.
- steep decline : the shell has become optically thin.
- plateau : Interaction with the ISM increase the radiation.

Expansion velocity evolution



Santamaría et al, 2020

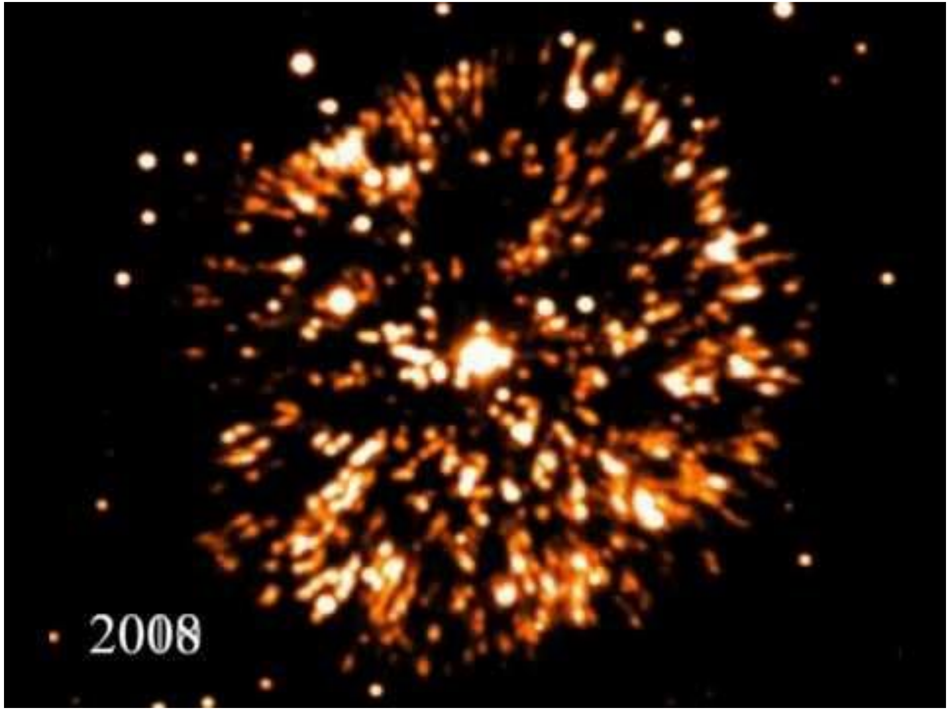
When nova shell starts to decelerate clear is not.

H.W. Duerbeck, 1987, studied 4 nova shells (V603 Aql, GK Per, DQ Her and V476 Cyg), and found evidence for deceleration in all of them (half-time of 65 yrs).

Santamaría et al, 2020, did not found evidence for deceleration of shells expansion.

Expansion velocity evolution

Nova shells will fragment as they expand and interact with the ISM.



Evolution of the firework nova shell, GK Per (337 pc), between 1953 and 2011.

Liimets et al, 2012

Mass of the ejecta

$$M_{shell} \sim 10^{-6} - 10^{-4}\ M_{solar}$$

It is usually stated that the mass of the ejecta is in the order of 10^{-6} to 10^{-4} solar masses, but how are these values estimated?

Mass of the ejecta

The ionized mass can be determined from the Balmer lines.
Required to know the electron temperature and density.

$$m_{\rm shell}(H^+) = \frac{4\pi\, D^2\, F(\mathrm{H}\beta)\, m_{\rm p}}{h\nu_{\mathrm{H}\beta}\, n_{\rm e}\, \alpha^{eff}_{\mathrm{H}\beta}\,(H^0, T_{\rm e})},$$

To determine T_e and n_e several lines ratios are needed.
This can only be achieved during the first stages after the nova eruption.

Sahman et al, 2018

Contribution to the ISM enrichment

Novae have a non negligible contribution to the enrichment of the galactic ISM.

	CNe	SNe
rate	35 / yr	0.02 / yr
ejected mass	10^{-4} M_{sol}	2 M_{sol}
total contribution	3.5 x 10^{-3} M_{sol} / yr	4 x 10^{-2} M_{sol} / yr

SNe contributes ten times more that SNe (and with heavier elements).
CNe are the most important contributors of ^{13}C, ^{15}N, ^{17}O.

Gehrz+98

What can be done with nova shells?

GK Per, credits: NASA

Expansion parallax

Expansion parallax is a technique that was widely used in era prior Gaia to determine distance to the Cataclysmic Variable.

$$R \sim 20\,\mathrm{arcsec}\,\frac{t/100\,\mathrm{yr} \times v/1000\,\mathrm{km\,s^{-1}}}{d/\mathrm{kpc}},$$

By measuring the speed at which the shell expands, it is possible to determine the distance.

If the shell has decelerated, the distance will be underestimated.

Sahman et al, 2015

Nova shells as evidence for ancient eruptions

People started to look for ancient nova shells around CVs with orbital periods mainly in the range of 3-5 hours.

In order to understand the effects of the nova eruption have in the CV during the decades and centuries after, it is necessary to look for systems that experienced a nova many centuries ago.

An additional test for the (dead?) Hibernation model

Nova shells as evidence for ancient eruptions

People started to look for ancient nova shells around CVs with orbital periods mainly in the range of 3-5 hours.

With surprisingly poor results : 2 new ancient shell from 148 systems.

Results has been used put constraints on the recurrence time (~13,000 yr, Schmidtobreick et al, 2015) or the nova like phase (~3000 yr, Sahman et al, 2022).

	Nova-like variables	Polars & intermediate polars	Asynchronous polars	Dwarf novae	Old novae	Total
Original paper (S15)						
WHT targets	22	1	2	2	4	31
IPHAS targets	5	10	2	34	23	74
Less: duplicated objects	−3				−1	−4
Total	24	11	4	36	26	101
This paper	39	1	3	3	1	47
less: duplicated objects	−12	−1	−3			−16
Total	51	11	4	39	27	132
Schmidtobreick et al. (2015)	5			10		15
Pagnotta & Zurek (2016)		1	3			4
less: duplicated objects			−3			−3
Grand total	56	12	4	49	27	148

Sahman et al, 2022

A diagnosis for the physics of nova eruption

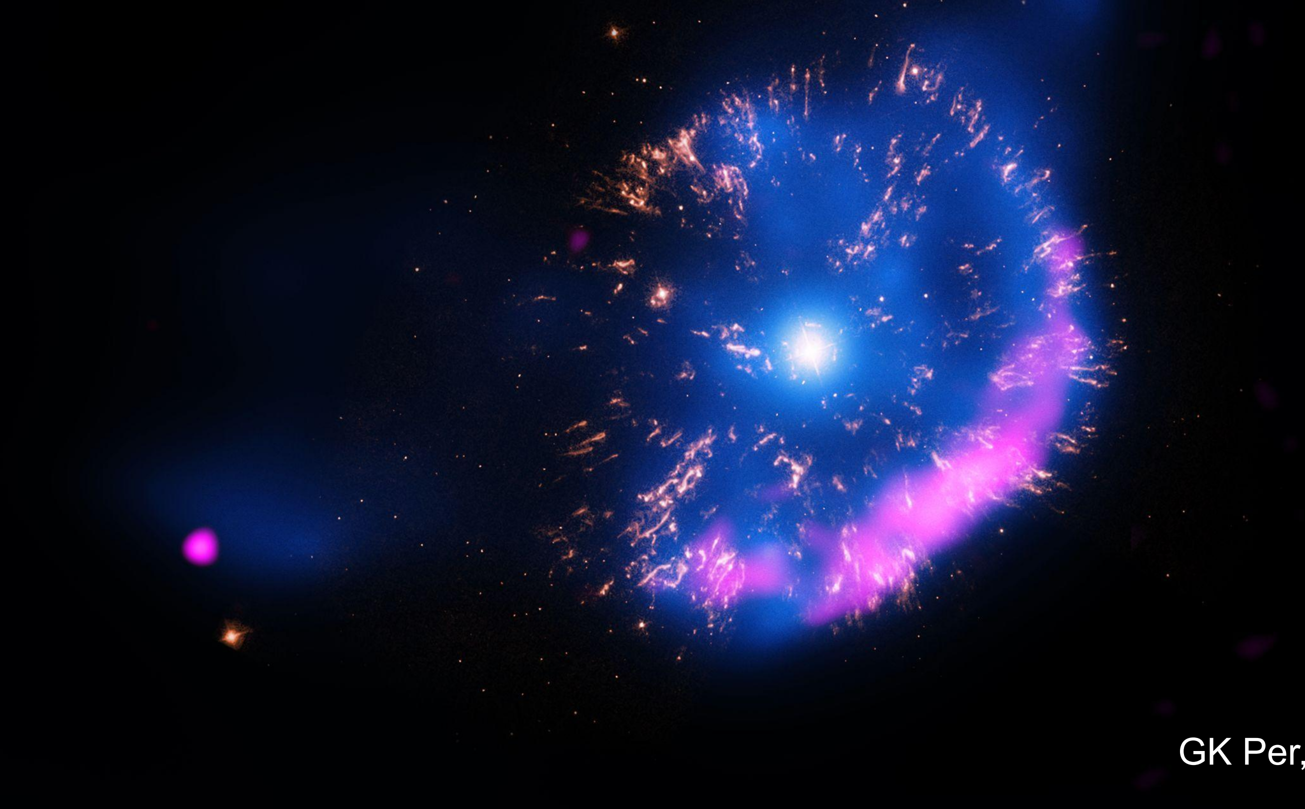
Nova shells work as diagnostic tools for our comprehension of nova eruptions.

Our theory of nova eruptions must be able to explain the different morphologies observed, and it does in the majority of cases.

But there is cases where is not.

A better understanding of this cases will help us to have a better picture of nova eruptions.

Some puzzling questions



GK Per, credits: NASA

Why so few ancient shells discovered?

Not clear why the surveys has given so poor results.

- Recurrence time is greater than expected
- Shells become fainter much faster that what is thought.

If shell luminosity evolves as t^{-3}, surface brightness will evolve as t^{-5} (assuming free expansion)!

A better understanding of how nova shells evolves will give us a better understanding of the reason behind.

* New observations reaching as deep as 27 mag/arcsec2 has been successful in this mission (Condor array, Shara et al 2024)

Not all novae create nova shells?

All novae should expel material into the ISM, creating a nova shell in the process, but..

Downes&Duerbeck, 2000, carries a search for nova shells around 30 post novae, failing at detect shells around 15 objects.

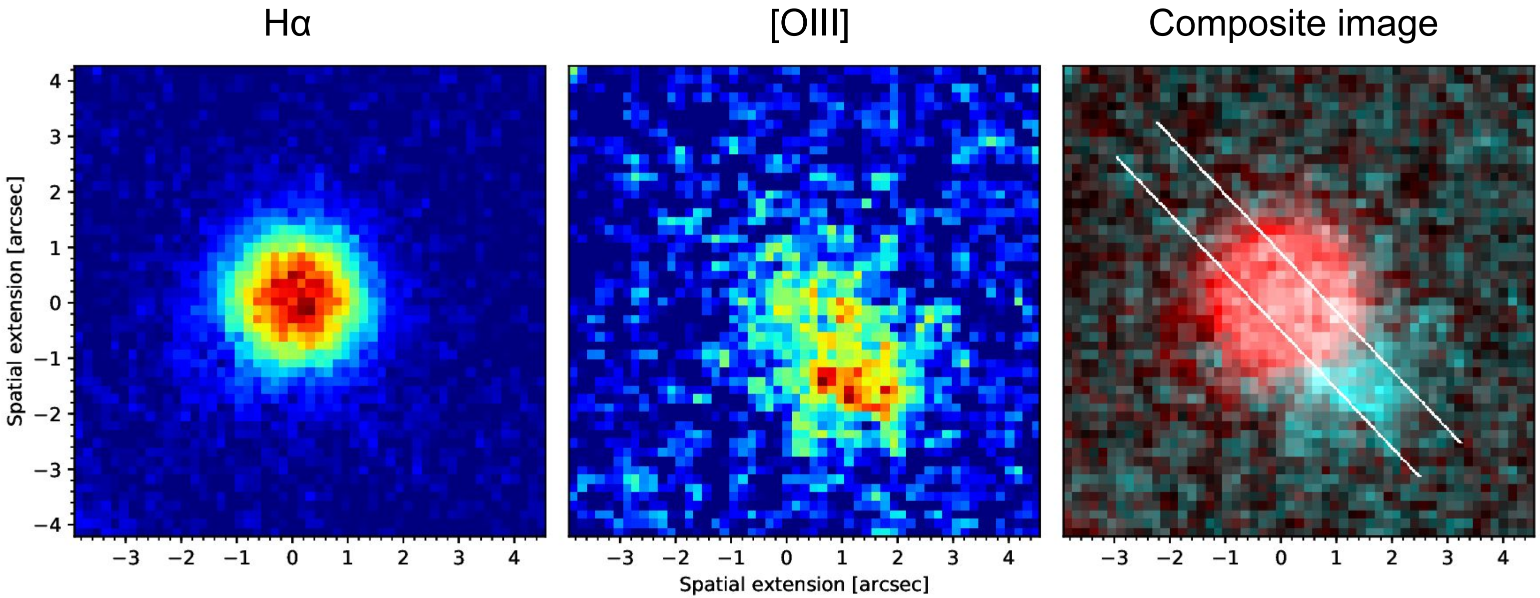
4 of them were too young to be resolved (inconclusive).

Upper limits ~10^{-16} erg/s/cm^2/arcsec^2 (too faint?)

Additional factors? (distance, environment..)

Asymmetries in young shells - V1425 Aql

V1425 Aql host an outer, faster and asymmetric shell observable in forbidden lines ([OIII] and [NII])



Tappert et al, 2023

Asymmetries in young shells - V1425 Aql

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A puzzling origin..

- The results of the interaction with the ISM.
- An asymmetric ejection.

Systematic asymmetric ejections could have an effect on the evolution of the Cataclysmic Variable

Tappert et al, 2023

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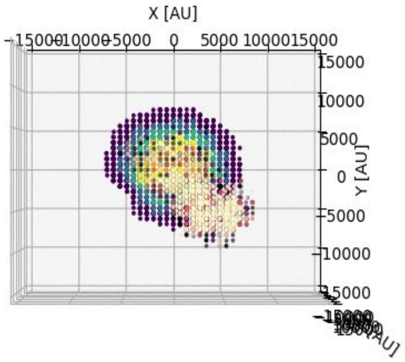
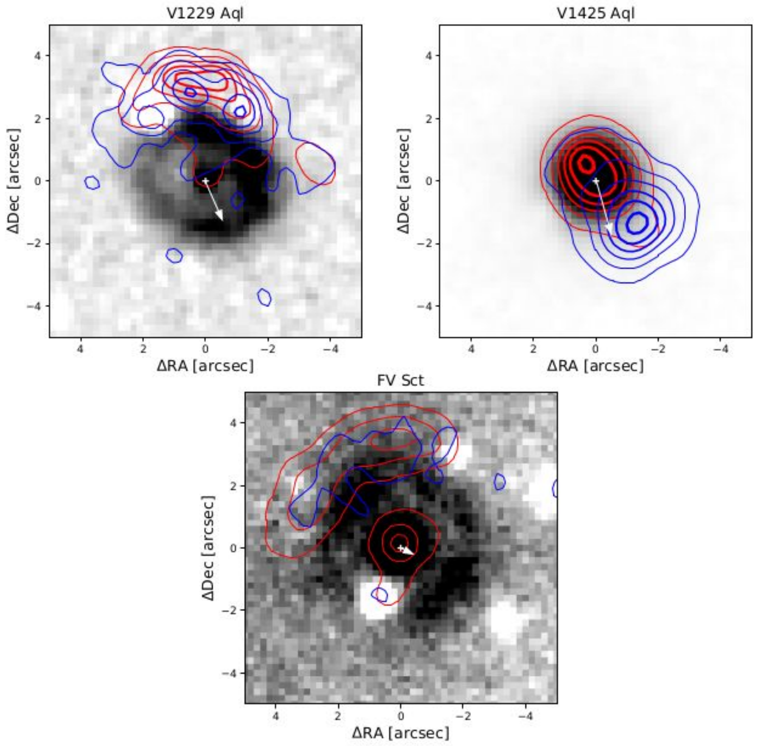


MUSE data reveals an arc-like structure for the outer shell.

Celedón et al, 2025

Asymmetries in young shells - FV Sct and V1229 Aql



In addition to V1425 Aql, two other asymmetric shells has been found. A not so rare phenomena that still lack of an explanation.

Ha, [NII], and [OIII] images of V1229 Aql, V1425 Aql, and FV Sct.
Celedón et al, in prep

Summary

As the remnants of nova eruptions, the study of nova shells help us to better understand the physical processes that take part during a nova but also the interaction with the surrounding ISM.

From the first days after the eruption, and hundreds of years later, nova shells show different kind of mechanism and interactions.

Our understanding of nova shells and nova eruptions is not complete, as there are cases which we can not fully explain.

Thank you for your attention