Cataclysmic Variables: A Universe of (non-fatal) Explosions

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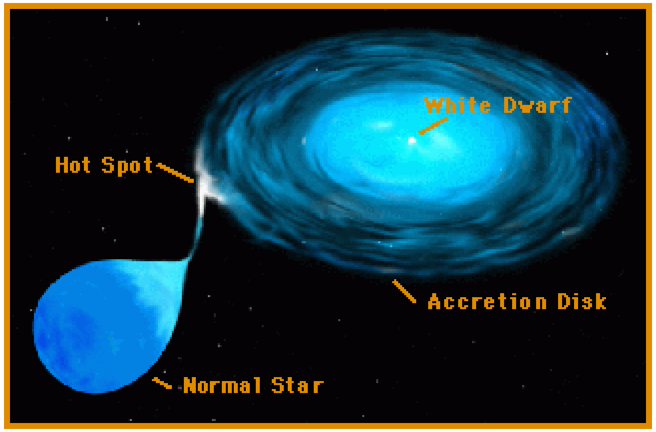
The CV Zoo

Cataclysmic Variables are interacting binary systems which contain a white dwarf primary and a companion (secondary) star, which is typically a lower-mass Main Sequence object (Red Dwarf), but sometimes a Red Giant.

Material is accreted from the companion onto the WD, via an accretion disc (unless the system is strongly magnetic).

There are many different types of CVs, most of which are seen to emit X-rays: (recurrent) novae, dwarf novae, nova-like variables and magnetic systems: polars and intermediate polars.



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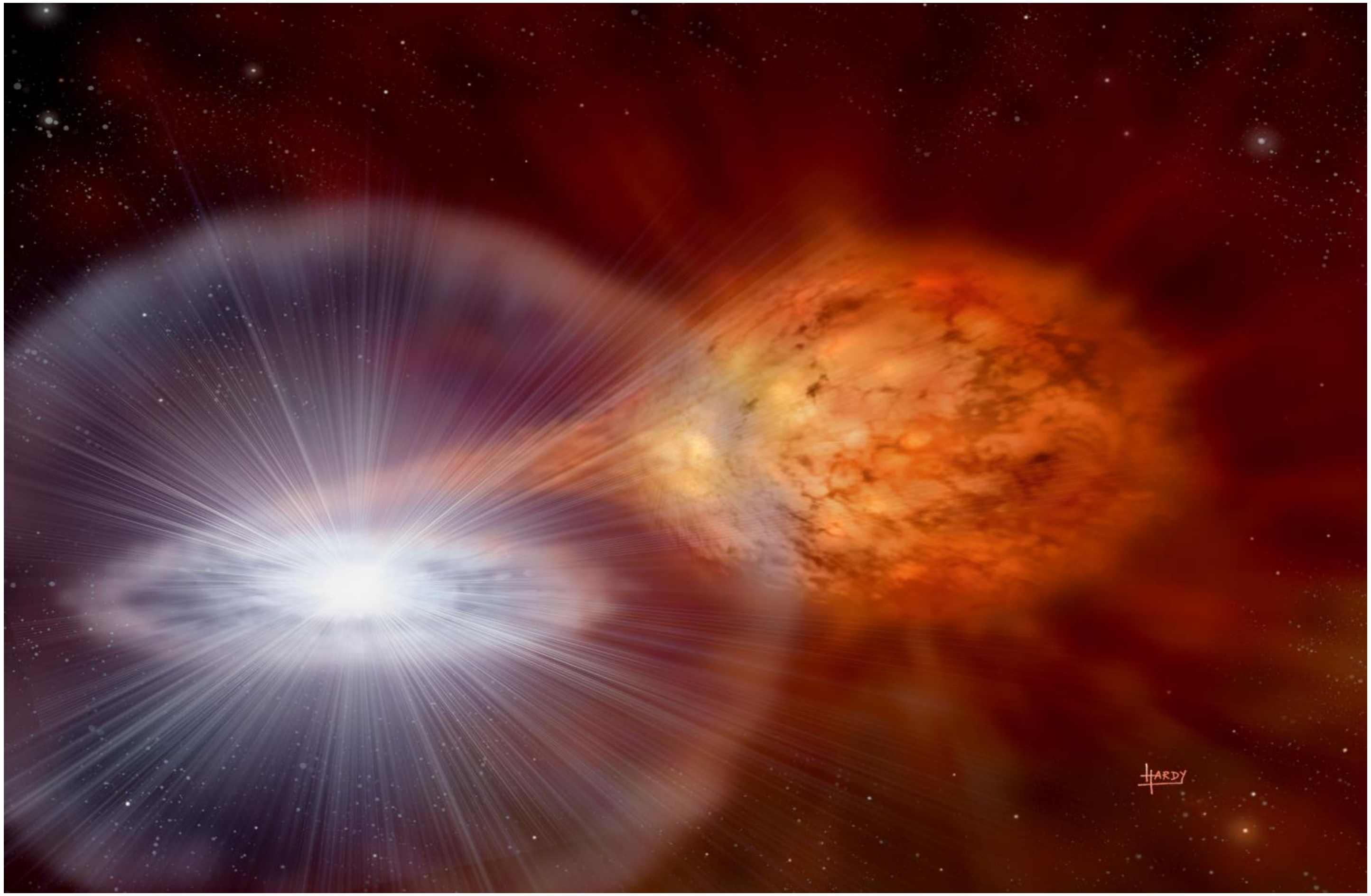
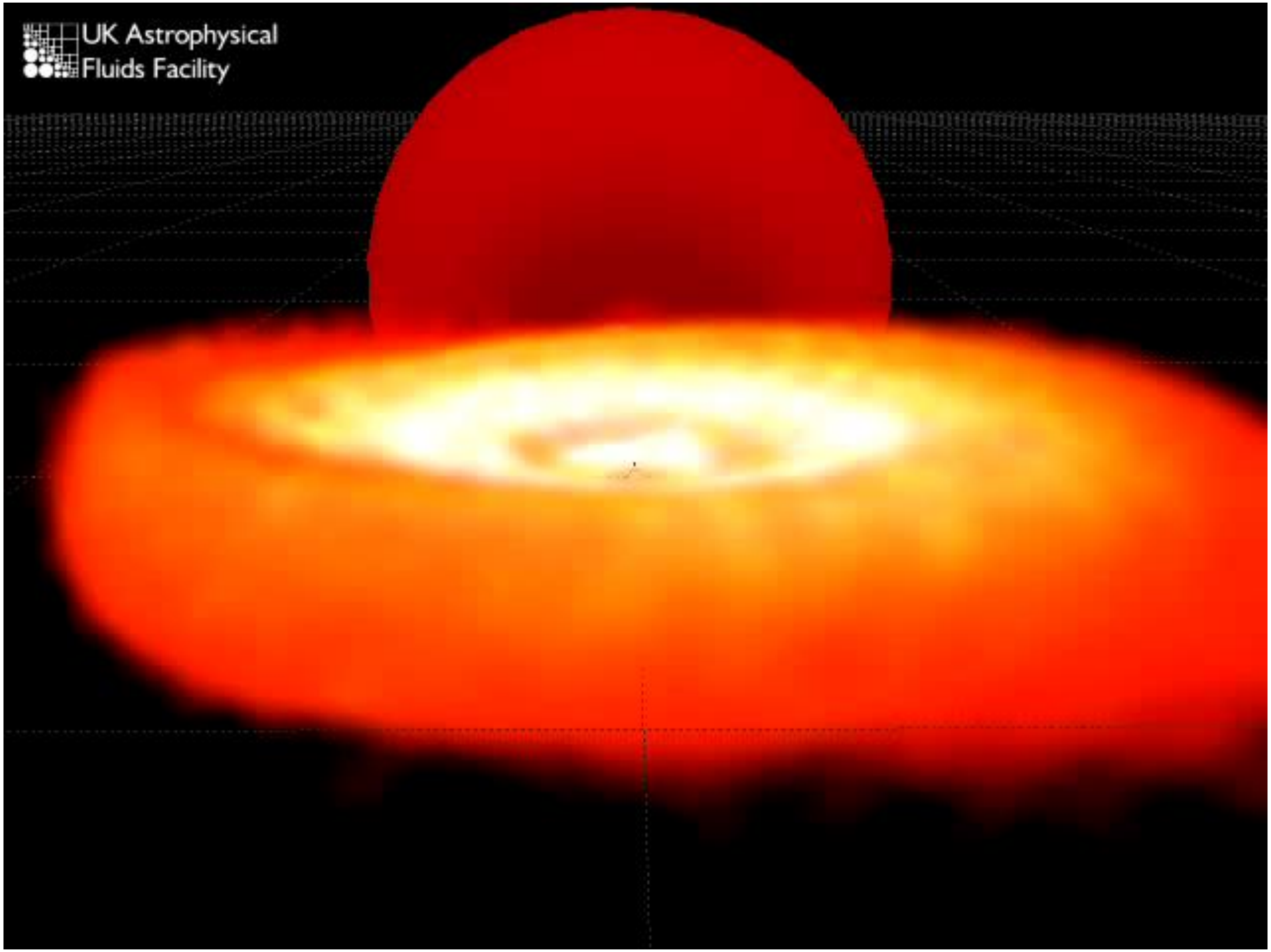


Credit: David Hardy/ www.astroart.org/STFC

Simulation of an accretion disc



Classifications

Type	Subsets	Outburst range	Time scale	Description	
Classical Novae		6 - >19 mag	~10,000 yr?	TNR on surface of WD. Single observed eruption.	
Recurrent Novae		4 – 9 mag	<80 yr	TNR on surface of WD. 2+ observed eruptions.	
Dwarf Novae	SU UMa	2 – 5 mag (some up to 8 mag)	Days to decades	Increased mass transfer through disc leading to large release of grav. P.E.	Show occasional superoutbursts.
	Z Cam				Show standstills when outbursts cease.
	U Gem				All other DNe.
Nova-Like Variables	SW Sex			All non-eruptive CVs. Disc in bright, high viscosity state (cf DNe outbursts). Usually stable mass transfer.	Highest NL mass transfer rates. Oddly single peaked emission lines.
	AM CVn				Permanent superhumpers. Accreting He.
	VY Scl				Anti-Dwarf Novae. (Show occasional reductions in brightness.)
Magnetic CVs	Polar (AM Her)			WD has a strong magnetic field which affects the accretion method.	Strongest mag. fields (10^7-10^9 G). WD spin synchronised to orbital period. No accretion disc.
	IP (DQ Her)				Lower mag. fields (10^6-10^7 G). Inner disc disrupted.

Novae

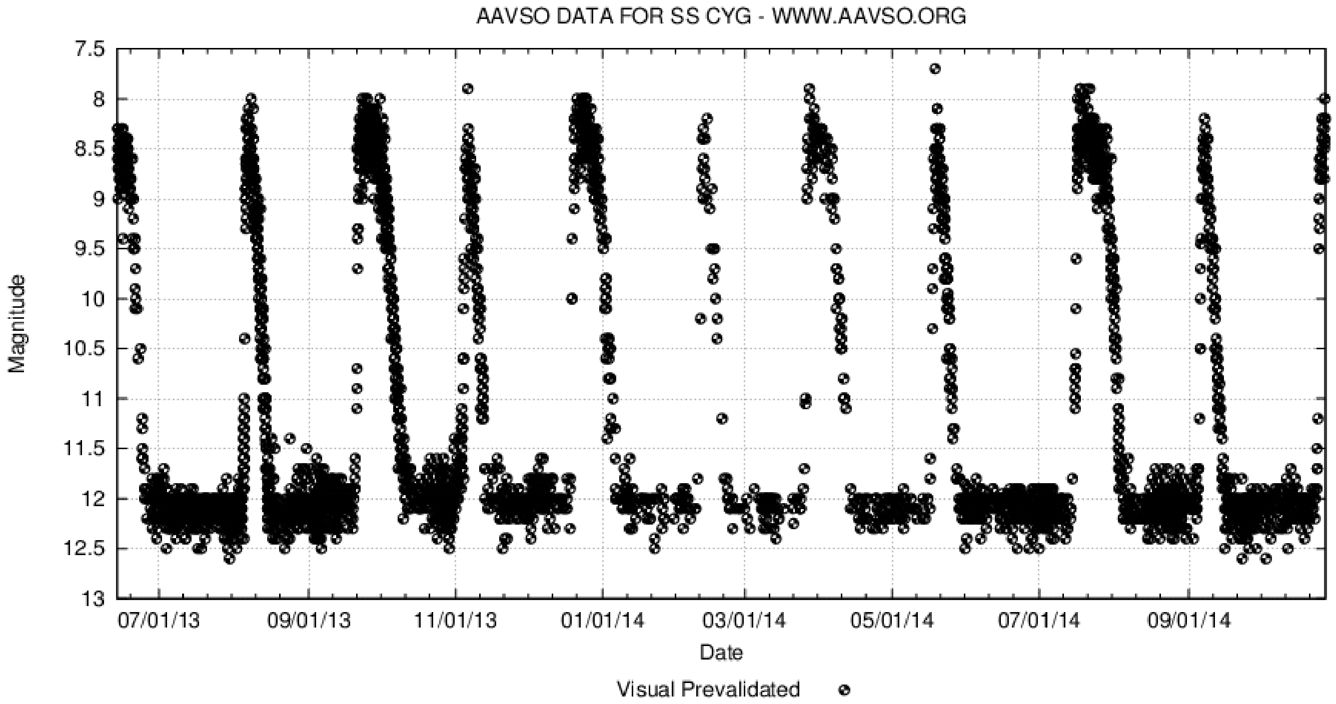
A nova is formed when sufficient hydrogen from the secondary star has been accreted on the WD surface, such that the pressure and temperature are great enough to ignite the material, leading to a thermonuclear runaway (TNR).

After the initial explosion is seen in the optical, the ejected material spreads out, becoming transparent enough to allow observations of the nuclear burning occurring on the surface of the WD. This appears as soft X-ray emission, and is therefore known as the Super-Soft Source phase.

Credit: Andy Beardmore (U. Leicester)

Dwarf Novae

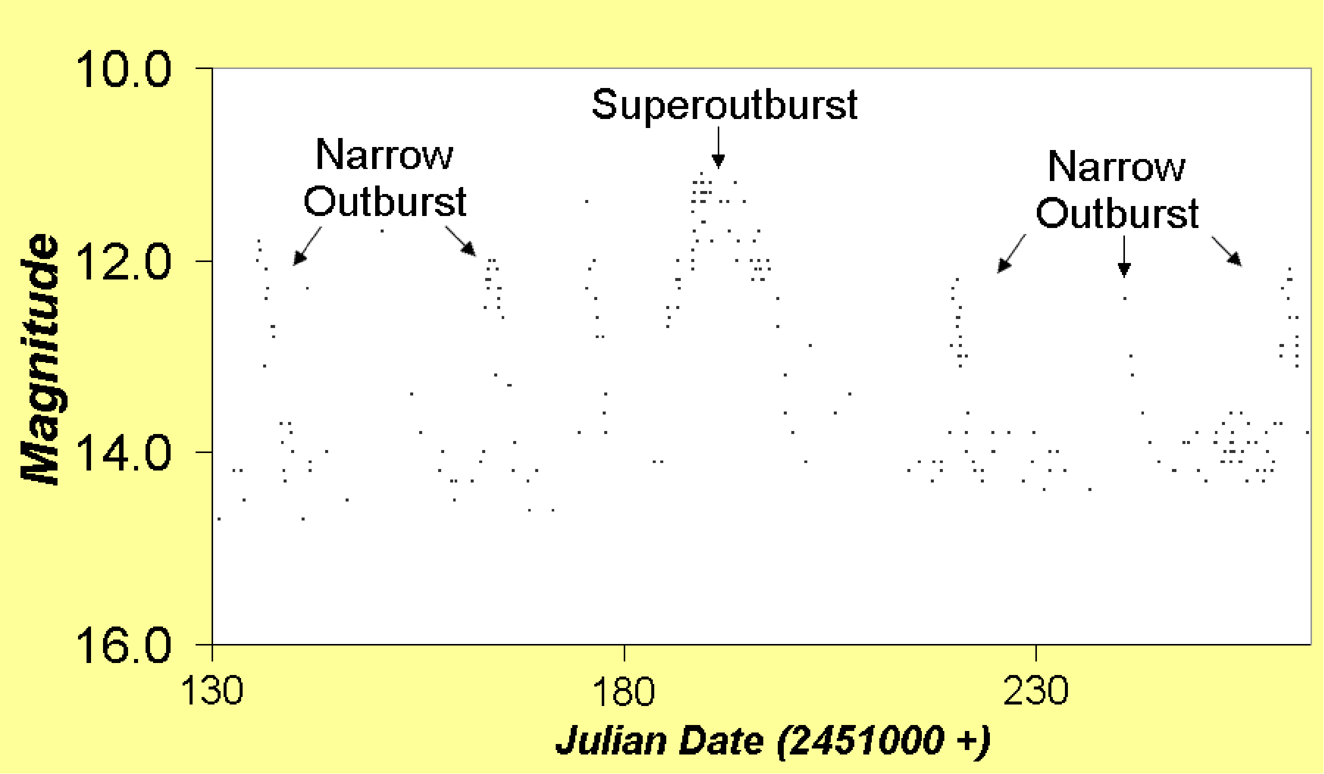
Dwarf Nova outbursts are caused by changes in the state of the accretion disc itself, not the stars. Material builds up in the disc until the density reaches a critical level, causing a change in the state of the accretion disc (partial ionisation of hydrogen). At this point the excess material is dumped onto the WD surface, releasing gravitational potential energy.



Credit: AAVSO

Dwarf Novae

SU UMa systems show additional “superoutbursts”. Not all of the excess mass is deposited onto the WD during a normal outburst, which means the accretion disc expands towards the secondary star. This leads to tidal interactions, distorting the disc into an elliptical shape.

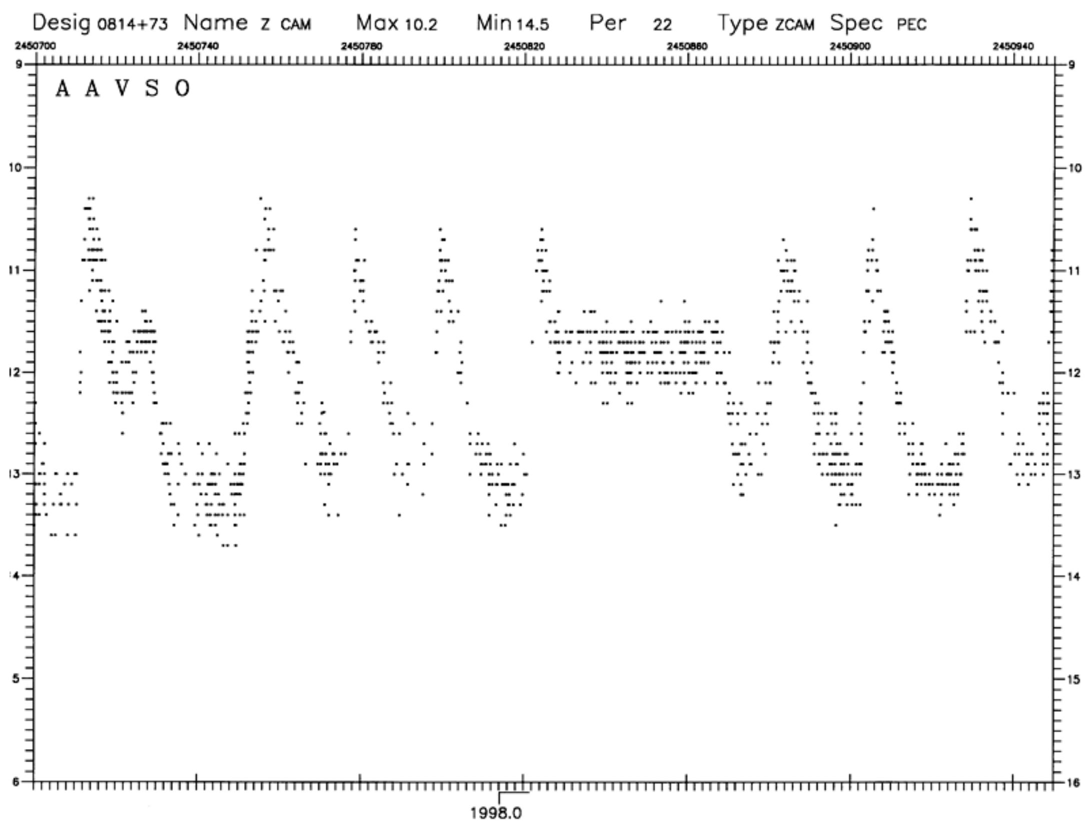


Credit: AAVSO

The disc precesses, forming a superhump period a few % longer than the orbit.
Tidal torques are enhanced, removing angular momentum from the disc, allowing it to shrink. A lot of mass is therefore lost onto the WD – which we see as a superoutburst.

Dwarf Novae

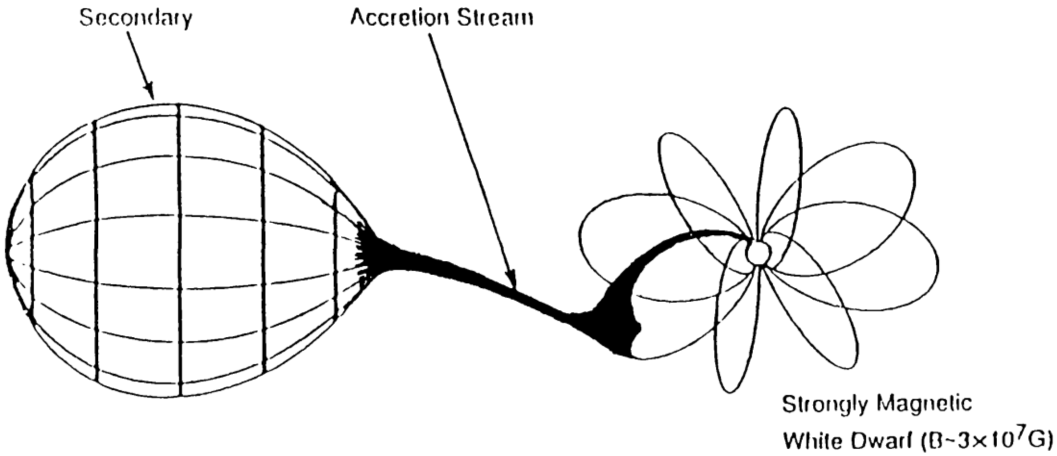
Z Cam stars sometimes show a standstill during their decline from outburst maximum. This is thought to be caused by the system being temporarily in equilibrium at a high (ish) mass accretion rate.



Credit: AAVSO

Magnetic CVs: Polars

If the WD in the binary system has a significant magnetic field, then a standard accretion disc cannot form since the moving charged particles create their own magnetic field. The accreting material therefore spirals around the WD field lines, and falls onto the magnetic poles of the WD.



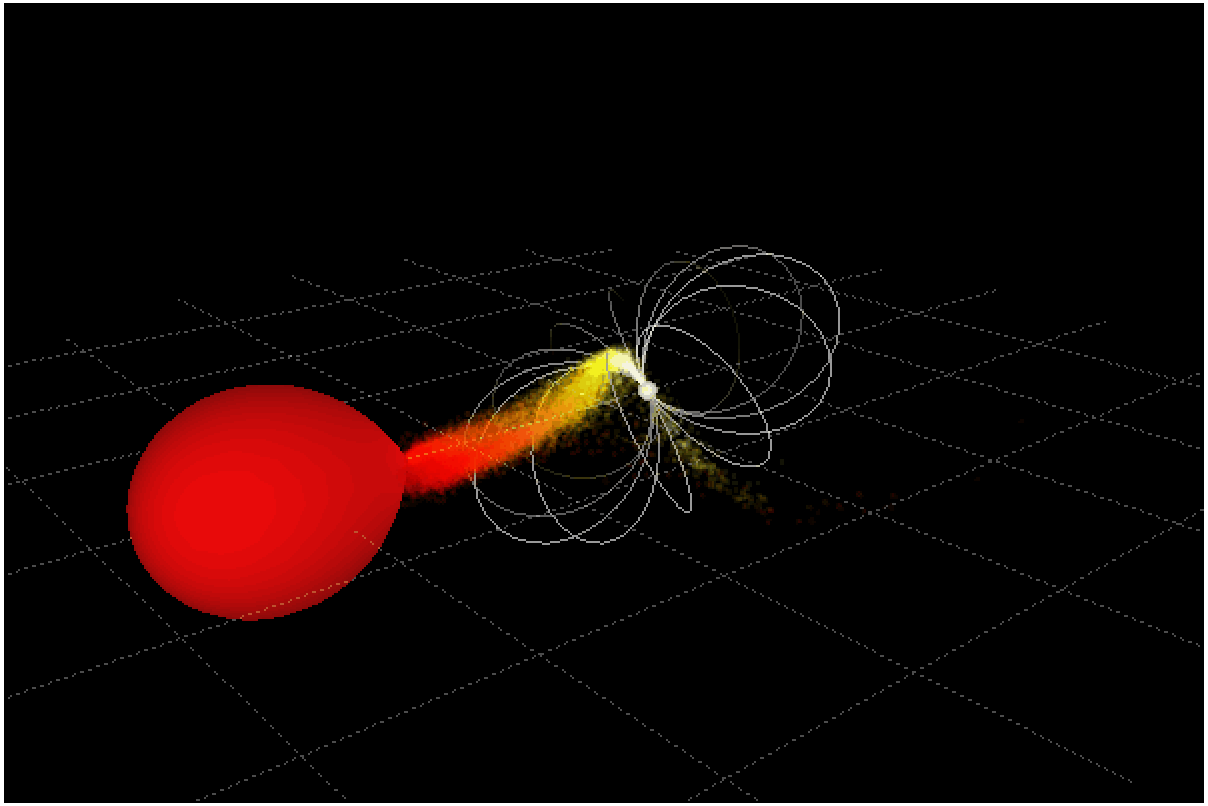
Shocks are formed when the accretion stream approaches the WD surface, leading to hard X-rays, most of which are reprocessed into softer X-rays.

In Polars the emitted light is both linearly and circularly polarised.

Spin and orbital periods are usually synchronised.

Credit: Cropper , 1990, SSRV, 54, 195)

Polar: EX Hya

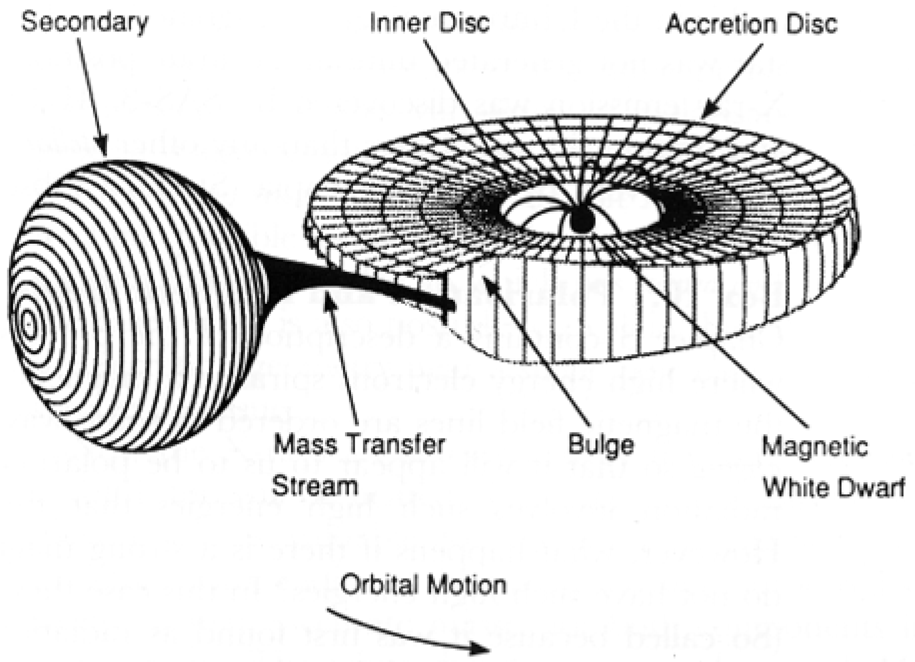


Credit: UKAFF. Simulation performed by Graham Wynn; visualisation by Richard West.

Magnetic CVs: IPs

The magnetic field in Intermediate Polars is not strong enough to synchronise the WD spin and orbital periods. An accretion disc can form, but the inner radius will be disrupted by the magnetic field. At this point the matter starts to stream along the magnetic field lines and onto the poles, as in the Polars.

IPs show both spin and orbital periods.



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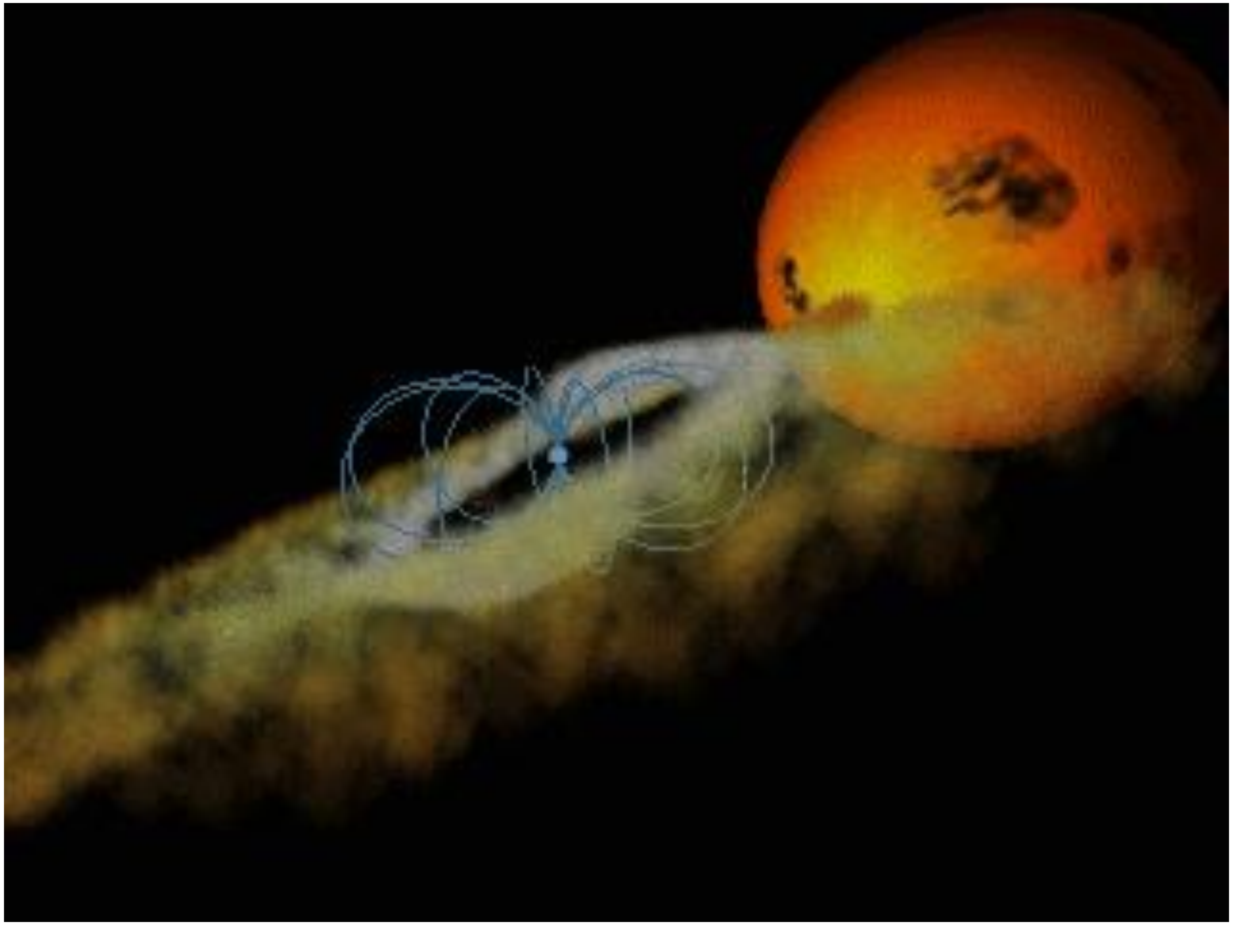
Intermediate Polar

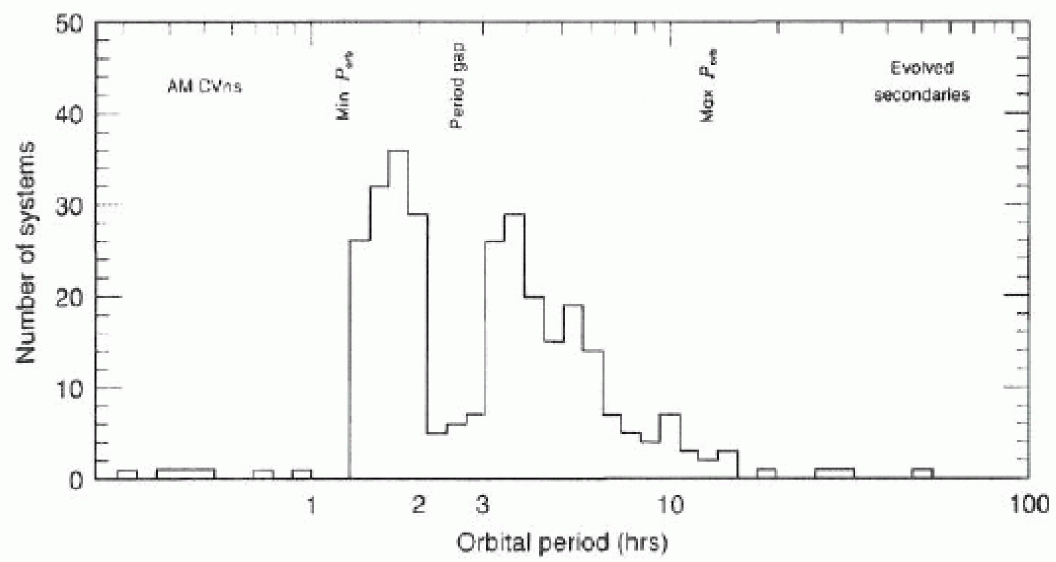


Credit: Andy Beardmore

CV Period Gap

Hellier (2001)

Lower mass transfer rate below Period Gap. (Grav. Radiation vs magnetic braking.)

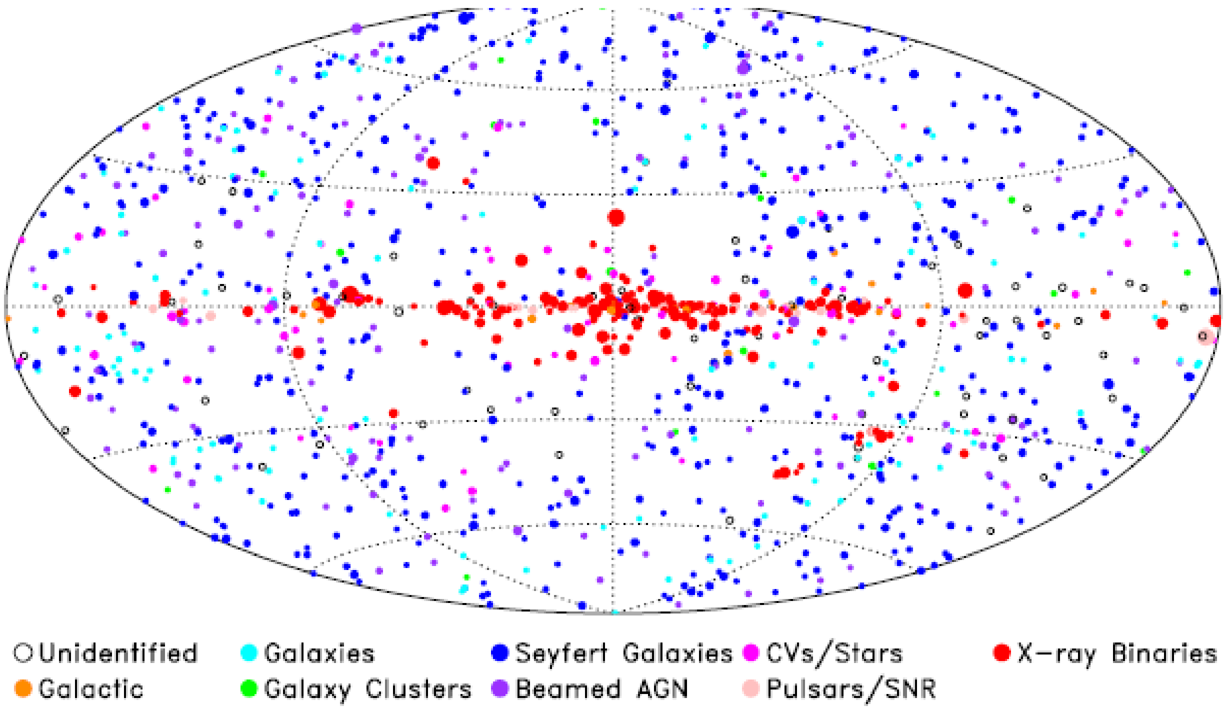


There is a dearth of CVs with orbital periods of 2-3 hours; this is the Period Gap.

The theory which sees CVs evolving from long (radiative core) to short systems, with the donor stars becoming fully convective at 3 hr cannot explain various observations of CVs (e.g. CVs should spend most of their lifetime near the min. period; ~95% of CVs should have P_{orb} < 2h). Our theoretical understanding of CVs is not complete (or observations very biased)!

Why X-rays?

X-ray sky surveys have shown many CVs to be X-ray sources.



All-Sky map showing hard X-ray sources detected by the Swift-BAT (Baumgartner et al., 2013)

So: what do X-ray observations of CVs and novae tell us?

Why X-rays?

The optical characteristics of a nova depend on the ejected envelope.
X-rays, however, allow us to investigate the WD itself.

X-rays are emitted in the boundary layer, where shocks are formed when the material has to slow down from the accretion disc velocities to the WD spin.

If the mass transfer rate is relatively low, the boundary layer is optically thin and the X-ray escape directly. At higher mass transfer rates, the boundary layer is optically thick, and both it and the inner disc are heated by the shocks, re-radiating as BBs.

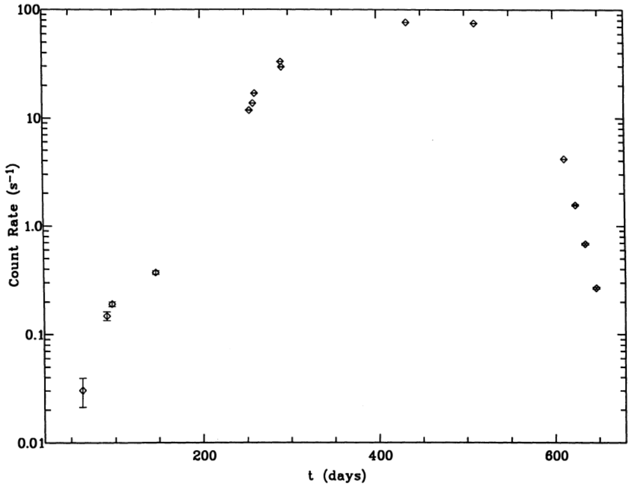
X-ray observations allow us to measure (or provide lower limits, depending on other cooling mechanisms) the mass of the WD and the mass transfer rate.

Grating observations provide line ratios, which allow us to measure the electron density and temperature, and the ionisation balance. Velocity broadening of the lines show whether the emission region is in the rapidly rotating boundary layer, or close to the more slowly rotating WD.

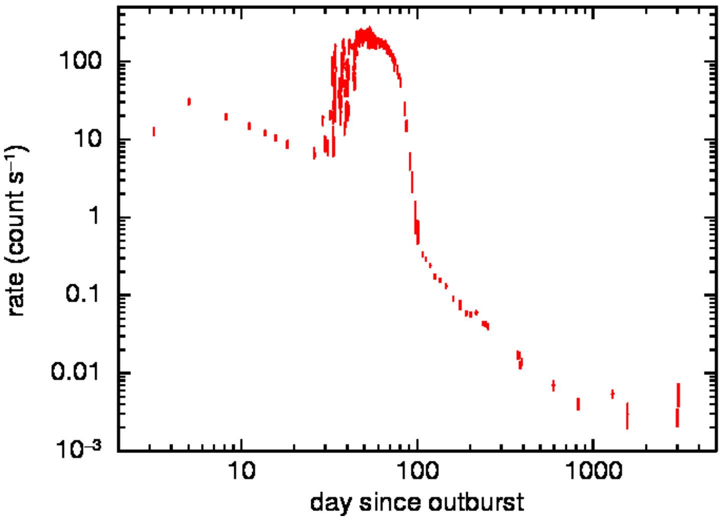
That was then… This is now!

The first X-ray detections of CVs were in the early 1970s, both with Uhuru (EX Hya; Warner 1972, 1973) and sounding rockets (SS Cyg; Rappaport et al. 1974).

Since then, with the advent of more sensitive X-ray satellites, the field has expanded hugely.



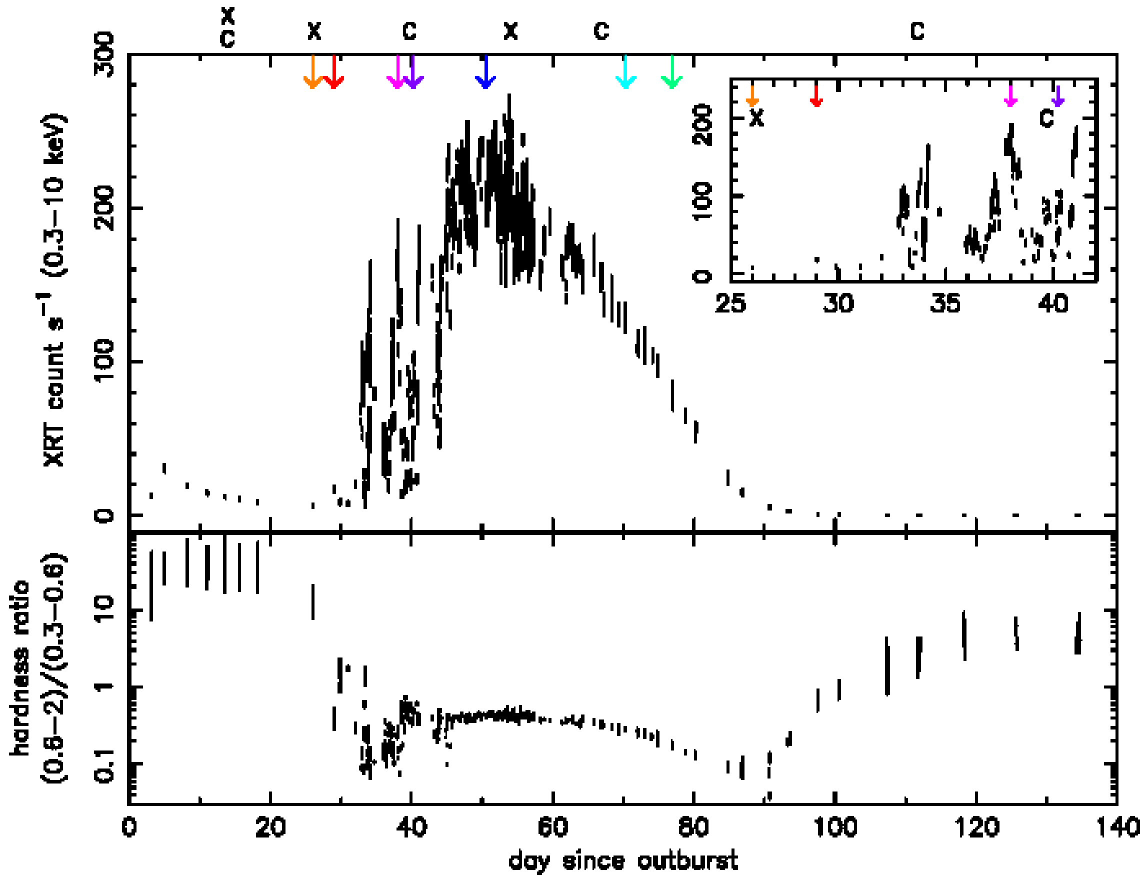
V1974 Cyg
(Krautter et al. (1996)



RS Oph

RS Oph: A Recurrent Nova

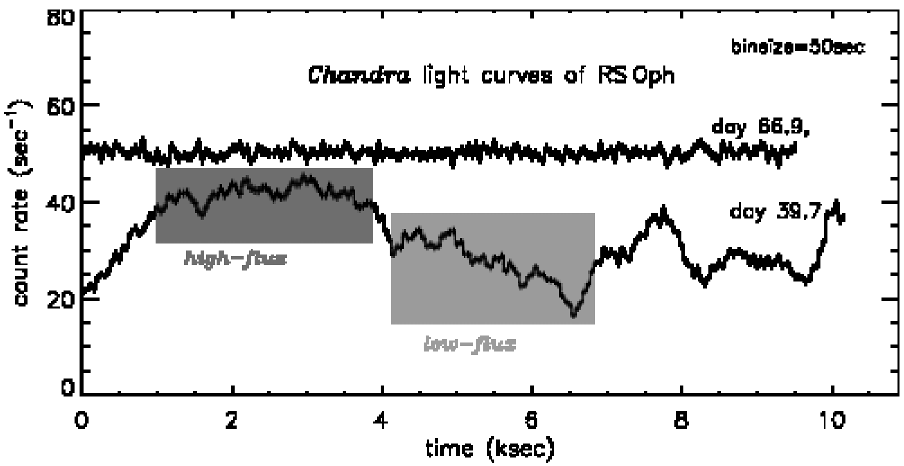
RS Ophiuchi is a RN with a recurrence time of ~20 years. The last outburst occurred in February 2006, and was monitored in the X-ray band for the first time.

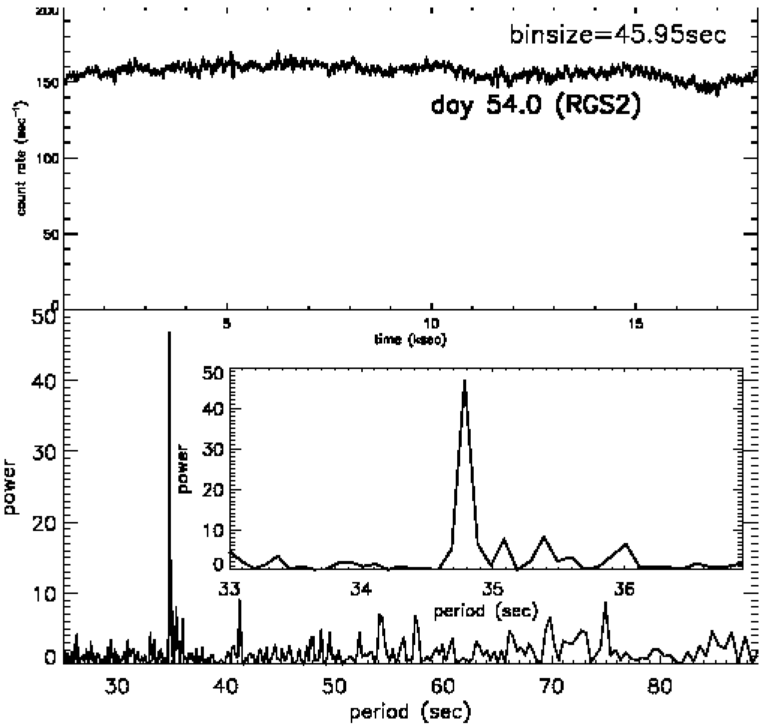


Osborne et al. (2011)

RS Oph

Chandra and XMM allow us to obtain long, uninterrupted observations, so both short- and long-term variability can be explored.



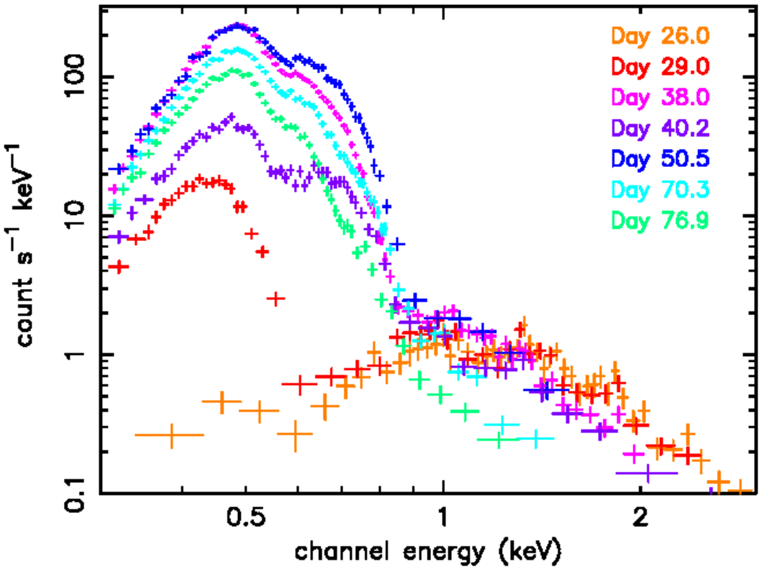


First identified in Swift data, then confirmed by XMM, RS Oph shows a ~35s QPO. Similar short period oscillations have since been found in other novae.

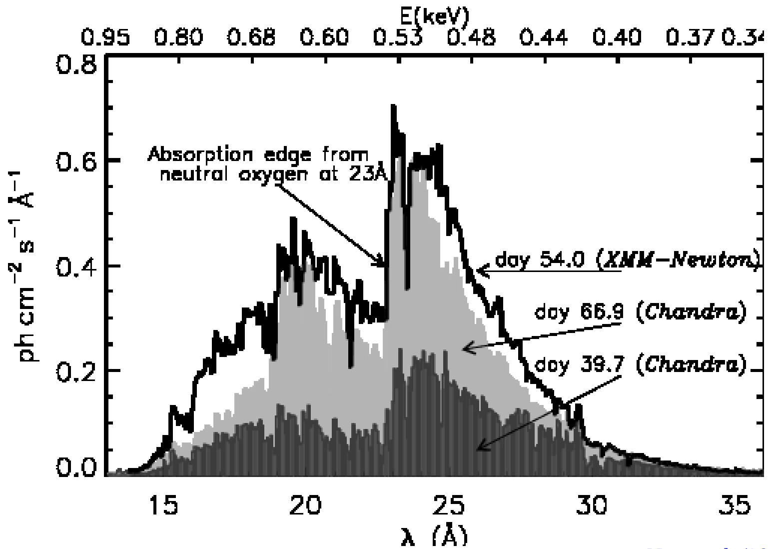
Ness et al. (2007)

RS Oph

RS Oph was the first time we were able to see in detail what the super-soft X-ray emission looks like in novae.



Osborne et al. (2011)

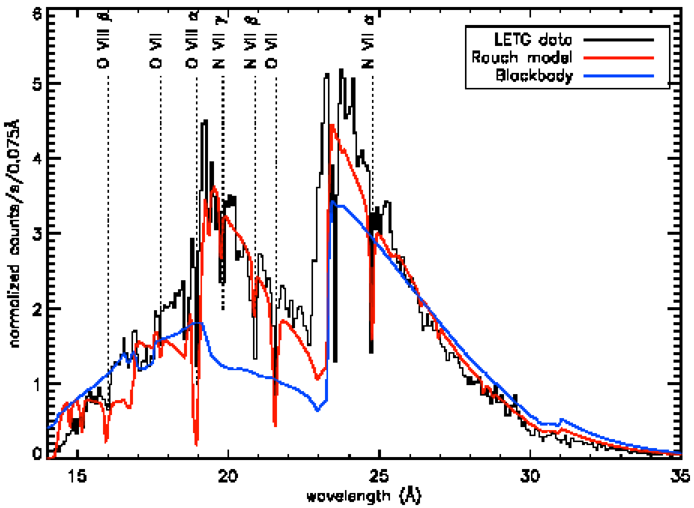


Ness et al. (2007)

CCD spectra give an idea of the underlying continuum shape, but gratings such as the RGS and HETG/LETG give much more detailed information about the emission and absorption features.

RS Oph

The X-ray emission during the supersoft phase looks very similar to a blackbody (especially in CCD spectra), sometimes with superimposed absorption edges. However, it has long been known that these are not physically sensible models. BBs under-predict the temperature and vastly over-predict the luminosity of the soft component (Krautter et al. 1996).



Nelson et al. (2008)

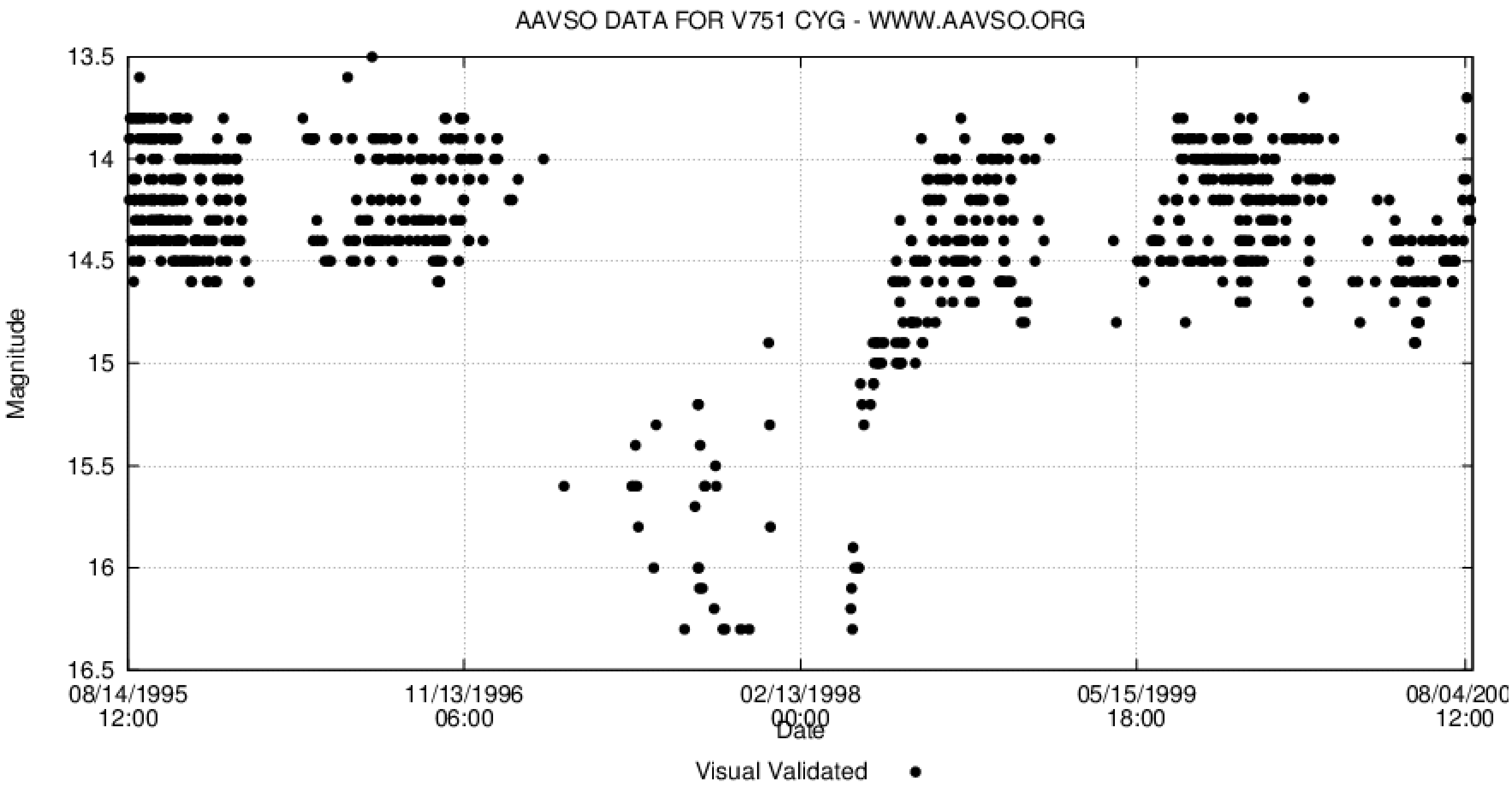
More realistic stellar atmosphere models are being worked on by various groups, though they are not yet perfect.

Models such as those by Thomas Rauch are plane-parallel, hydrostatic NLTE parameterisations.

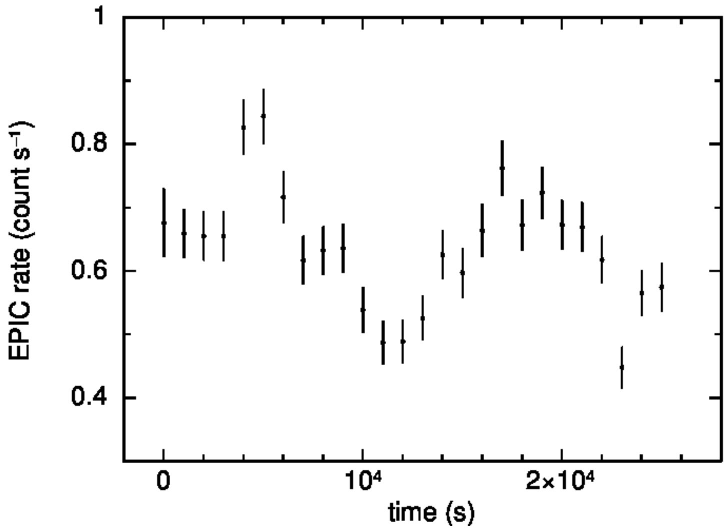
Daan van Rossum creates spherically symmetric, expanding atmosphere grids, which are a further step in the physical direction.

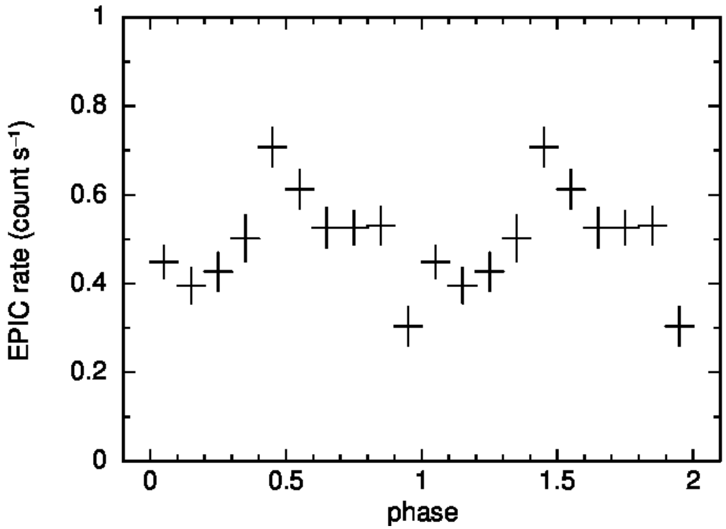
V751 Cyg: An Anti-Dwarf Nova

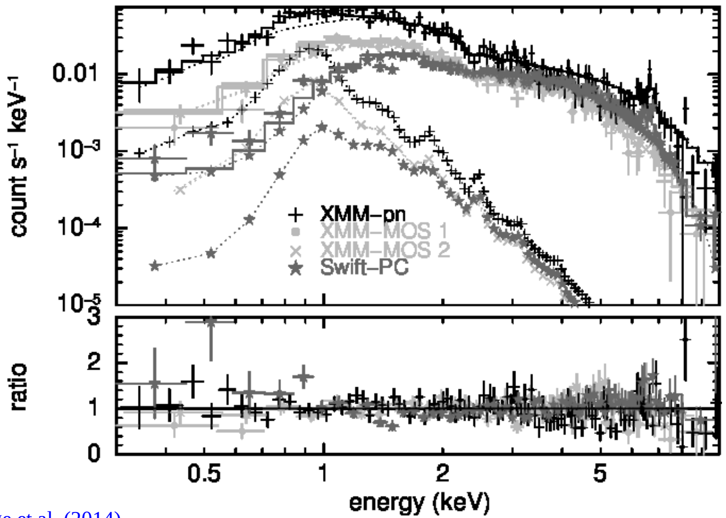
During the creation of the 3XMM-DR4 catalogue, a serendipitous observation of V751 Cyg was identified. The source showed a hard spectrum and apparent variability.



V751 Cyg







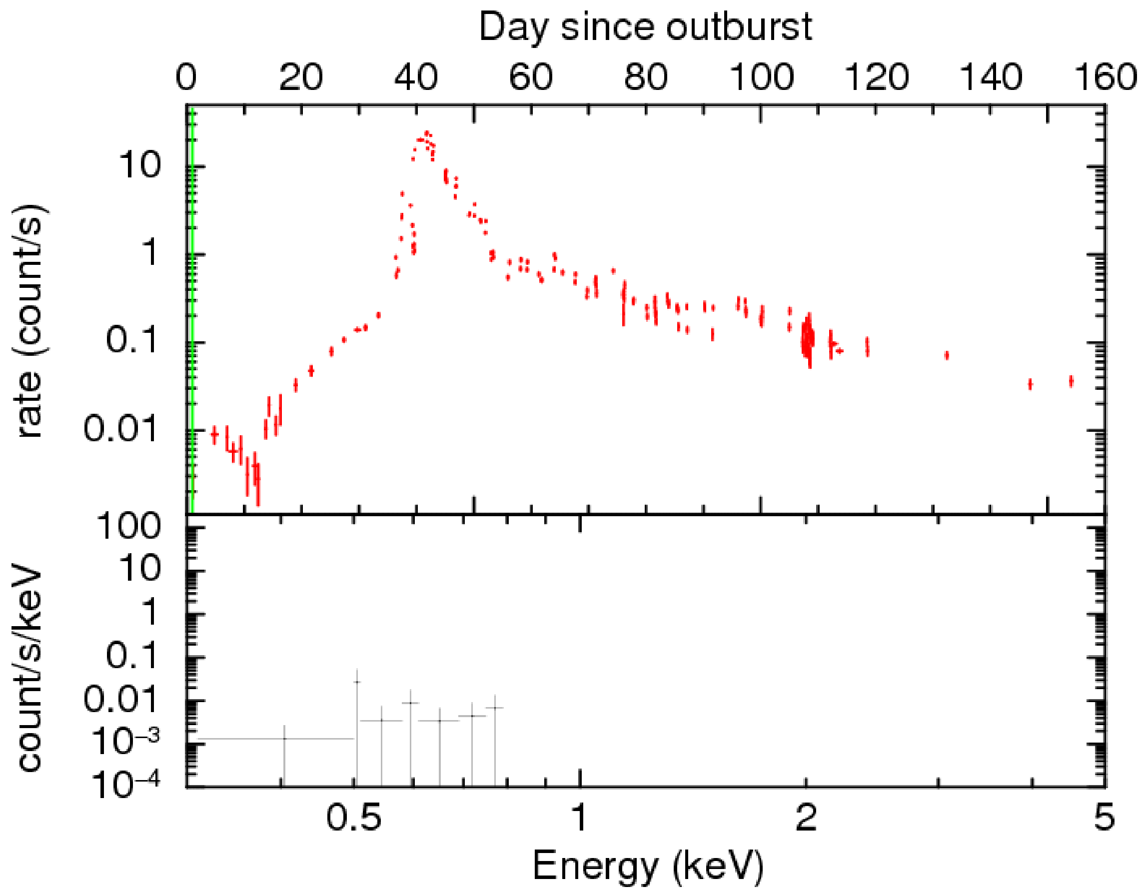
Page et al. (2014)

The modulation shown in the X-rays is at the known orbital period of 3.467 hr. It had not been reported in the X-ray band before, though.

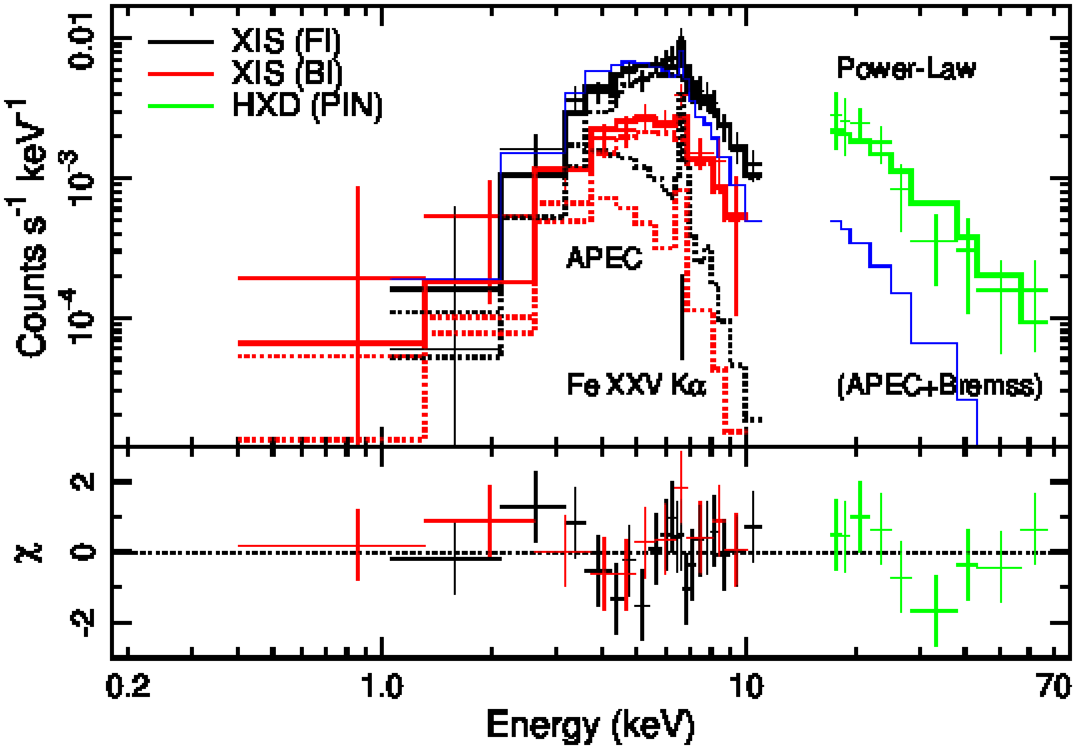
The spectrum can be well fitted by 2 optically-thin emission components, with significant absorption.

V2491 Cyg: Nova, Recurrent, IP?

V2491 Cyg was the second nova discovered in the constellation of Cygnus in 2008 (= Nova Cygni 2008 No. 2). Actually detected pre-outburst in archival Swift data.



V2491 Cyg



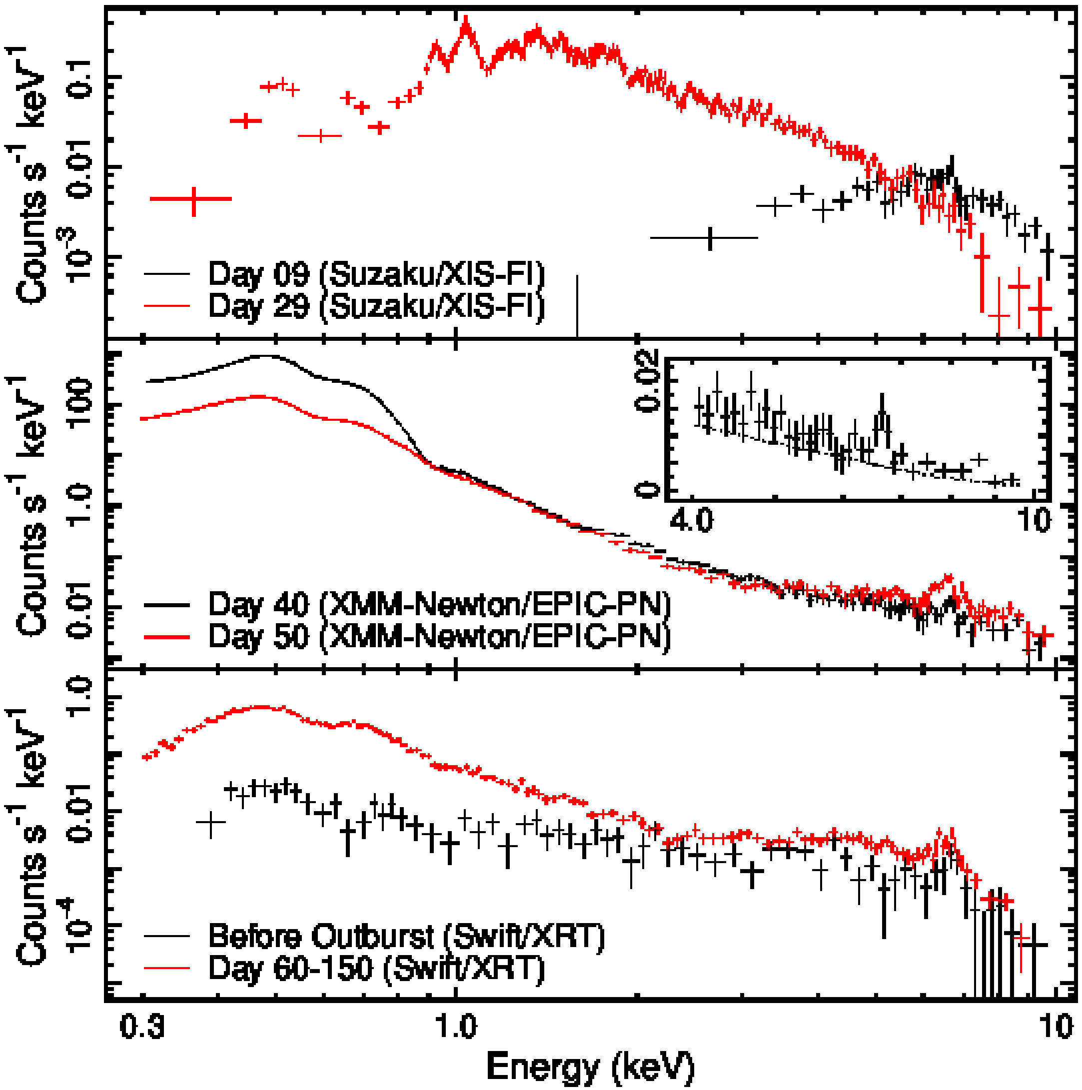
Suzaku found superhard emission, extending up to 70 keV on day 9 (but not day 29) after the outburst.

This is modelled as a combination of a ~3 keV thermal plasma and a flat power-law (Γ ~ 0.1).

Takei et al. (2009)

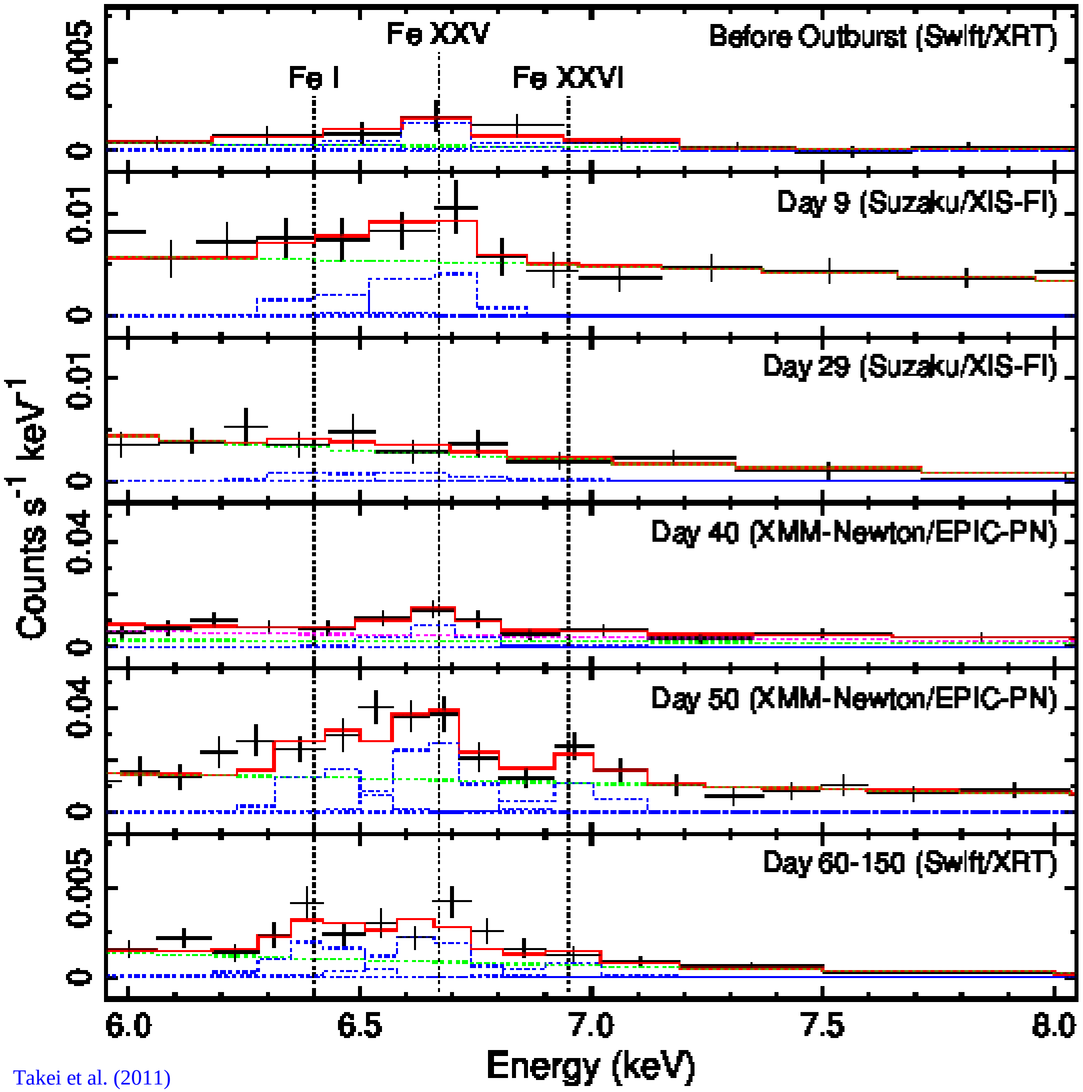
Following the launch of Fermi later in 2008, 6 novae have been detected at GeV energies! (V407 Cyg, V1324 Sco, V959 Mon, V339 Del, V1369 Cen, V745 Sco)

V2491 Cyg



Takei et al. (2011)

V2491 Cyg



Takei et al. (2011)

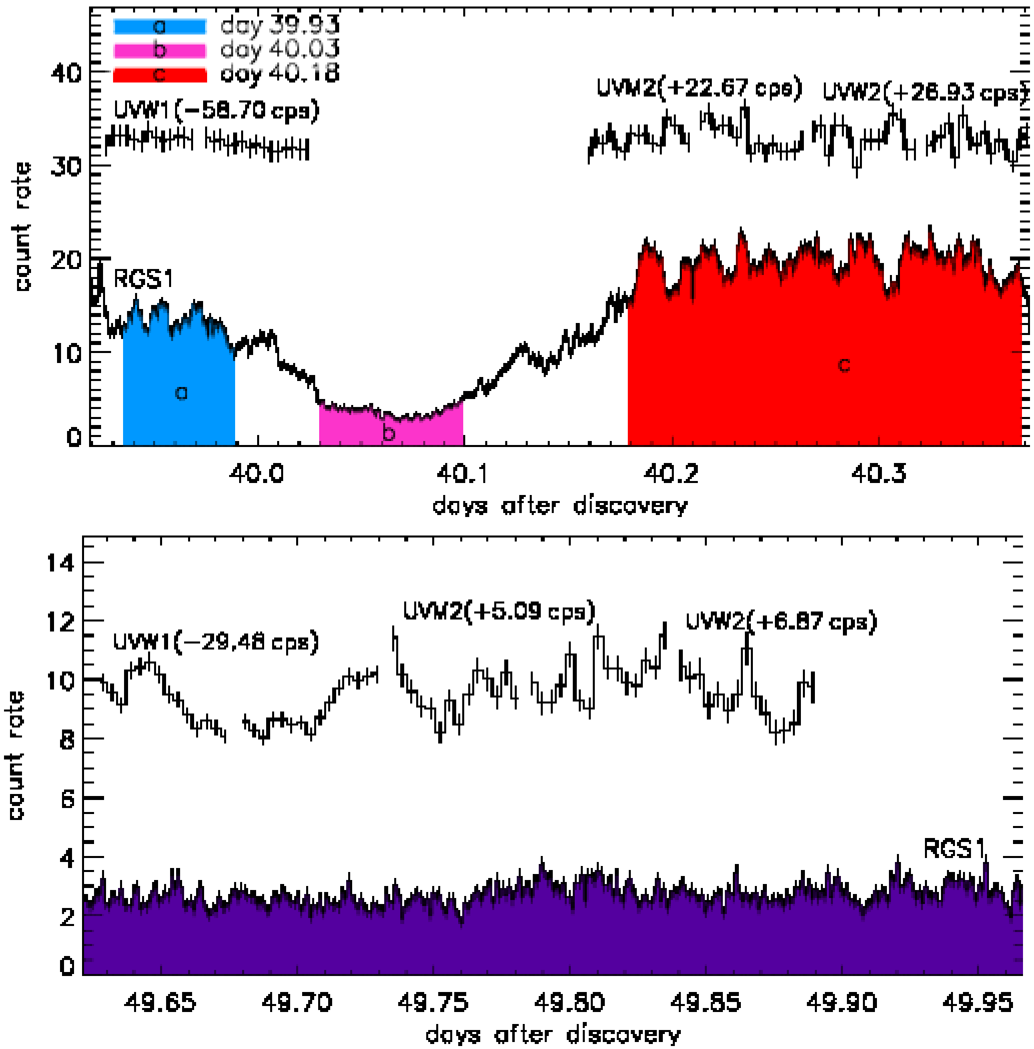
During the day 9 observation, the Suzaku spectrum showed a significant 6.7 keV ionised Fe line, but this was gone by day 29.

However, XMM data collected on day 40 again revealed a 6.7 keV line.

At later times (day 50+), iron emission at 6.4, 6.7 and 7.0 keV was detected.

Early on: X-ray emission from shocks in the ejecta.
Later: rekindled accretion.
Accretion re-established ~day 50.

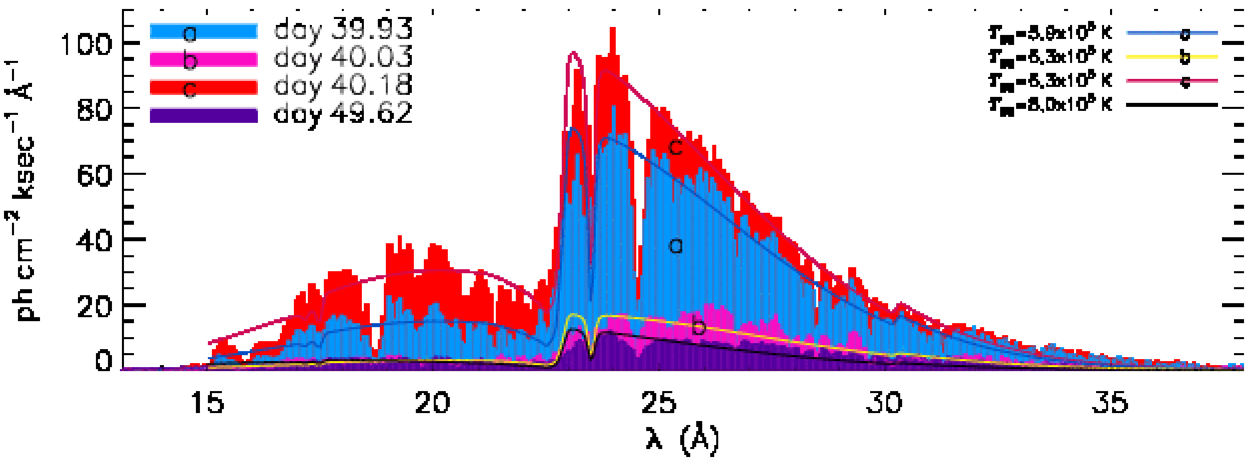
V2491 Cyg



X-ray light-curve is definitely variable, with a possible period of 37.2 min.

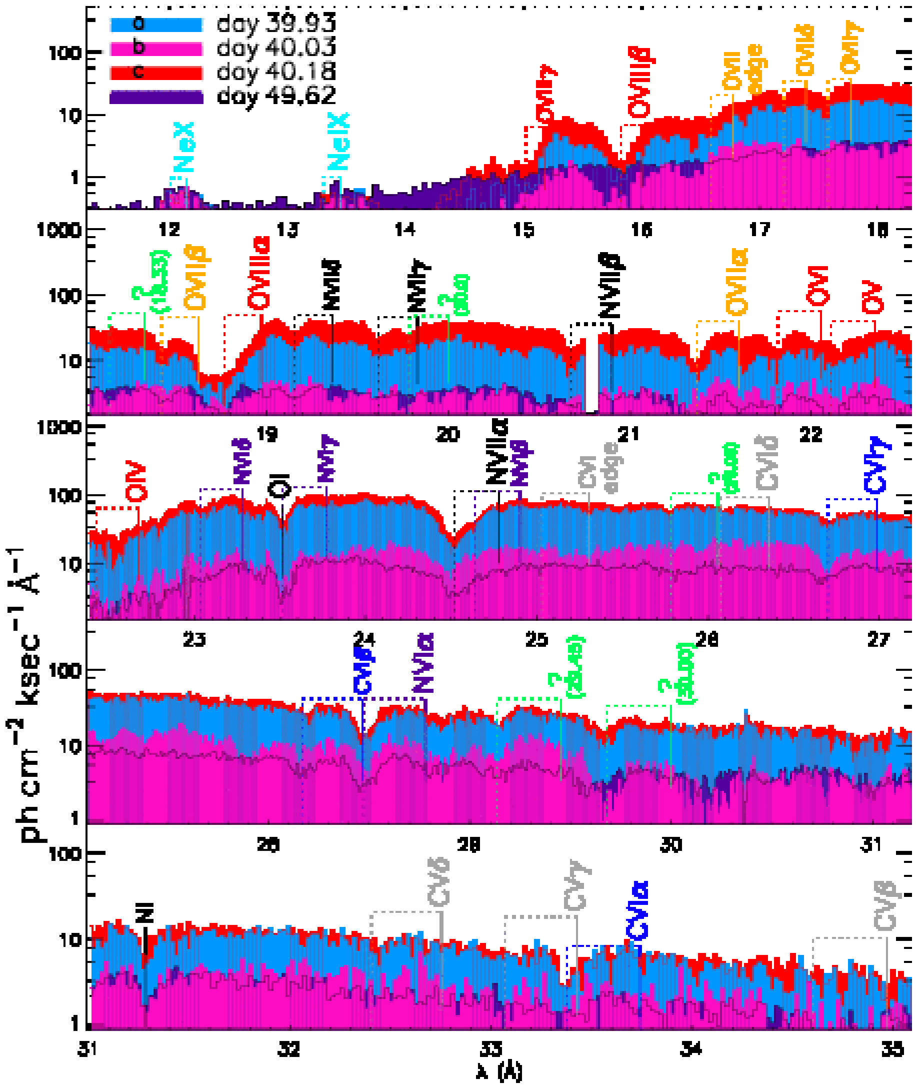
Ness et al. (2011)

V2491 Cyg



Roughly parameterising the spectra with BB continua.
They show deep absorption lines and edges, though.

V2491 Cyg



Most lines appear to be blue-shifted, indicating an expansion velocity of about -3200 km s^{-1}.

They are also broadened (not just instrumental), showing the ejecta are extended.

Grey lines are not detected, but are of interest.

V2491 Cyg

Is V2491 Cyg an Intermediate Polar (ie a magnetic system)?

- Detection of X-rays in quiescence – although also seen in RNe
- Fe line emission
- Possible multiple period detections (X-ray and optical) – spin and orbital? The longer period seen in the optical is not, however, detected in the X-ray band.

Since in an IP system the accretion disc is partly disrupted, a shorter time is required for its reformation (the disc doesn't have to form all the way down to the WD surface) and therefore the resumption of accretion can be more rapid.

Summary

The term "Cataclysmic Variables" covers a wide range of interacting binary star systems:

- some dominated by accretion energy, others by temporary nuclear fusion
- some regularly going into outburst, others seen in outburst just once (or never)
- some with strong magnetic fields, others with negligible field strengths
- orbital periods from ~80 minutes to ~ 12 hours (< 6 hr typically).

CVs include all types of accretion discs:

- optically thin versus optically thick
- face-on versus edge on
- non-steady versus nearly steady state

Hundreds of CVs are already known, and many new novae are being discovered every year, so there are plenty of data to keep us busy!