*Binary Paths to Type Ia Supernovae Explosions*
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# *Swift* Observations of Novae

**K. L. Page**

Department of Physics and Astronomy, University of Leicester,
University Road, Leicester LE1 7RH
email: kpa@star.le.ac.uk

**Abstract.** The rapid response capability of *Swift*, together with the daily planning of its observing schedule, make it an ideal mission for following novae in the X-ray and UV bands. A number of both classical and recurrent novae have been extensively monitored throughout their supersoft phase. We report findings from these observations, including the high-amplitude flux variation often seen at the start of the supersoft emission, the optical plateau sometimes seen for recurrent novae, the differing relationships between the X-ray and UV variability, and the turn-on and turn-off times of the supersoft emission for the *Swift* sample of novae.

**Keywords.** novae, cataclysmic variables

## 1. Introduction

A nova is a thermonuclear explosion on the surface of a white dwarf (WD), which occurs when enough matter has been transferred from the secondary star such that the pressure and temperature at the base of the envelope of accreted material is sufficiently high. Part of the envelope is then expelled, obscuring the X-rays being emitted from the WD surface. Once this material has become optically thin, the surface nuclear burning becomes visible, peaking in the soft X-rays: the so-called supersoft source (SSS) phase.

Although *Swift* (Gehrels *et al.* 2004) was designed as a Gamma-Ray Burst Explorer, its rapid response capability and daily planning of its observing schedule also make it ideal for prompt follow-up and monitoring of transient sources such as novae. Using the co-aligned X-ray (XRT; Burrows *et al.* 2005) and UV/Optical (UVOT; Roming *et al.* 2005) telescopes, simultaneous light-curves over these bands can be obtained, allowing the investigation of broadband variability. In the following sections, we discuss some of the findings from the *Swift* observations.

## 2. Setting the Scene

Before the launch of *Swift*, the *ROSAT* observations of V1974 Cyg (Nova Cyg 1992; Krautter *et al.* 1996), comprising 18 pointings obtained between 63 and 653 days after the outburst, provided the most detailed study of the X-ray light-curve of a nova. As the left-hand panel of Figure 1 shows, the X-ray light-curve revealed a monotonic increase for the first few hundred days, followed by an interval where the count rate was approximately constant and then a final drop-off in flux. This was also the brightest SSS in terms of observed flux measured at this time. In February 2006, the recurrent nova (RN) RS Oph went into outburst (references in Evans *et al.* 2008) and a *Swift* monitoring campaign was begun, a mere 3.2 days after the discovery of the outburst. The right-hand panel of Figure 1 shows the fantastically detailed light-curve obtained, with the nova being followed for more than 1500 days (Osborne *et al.* 2011). This light-curve showed that the rise-constant-fall pattern seen in the V1974 Cyg X-ray emission was an over-simplification of the emission occurring.

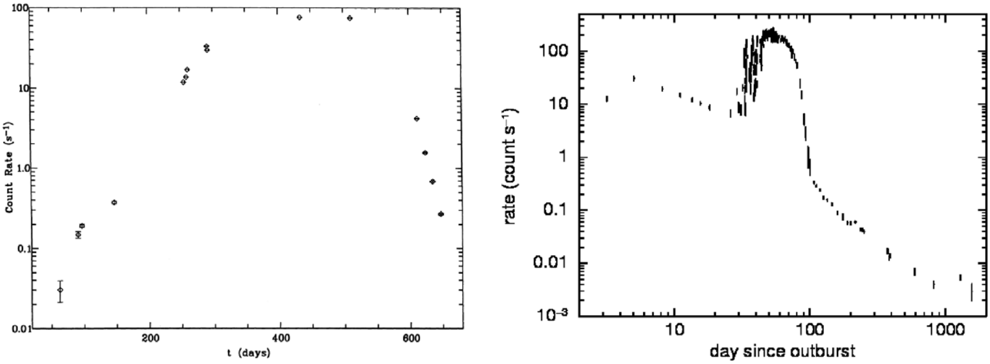


**Figure 1.** Left: The *ROSAT* light-curve of V1974 Cyg (taken from Krautter *et al.* 1996), which had the best temporal coverage and brightest SSS detected prior to the launch of *Swift*. Right: The X-ray light-curve of RS Oph (Osborne *et al.* 2011), the first detailed monitoring campaign of a nova performed by *Swift*.

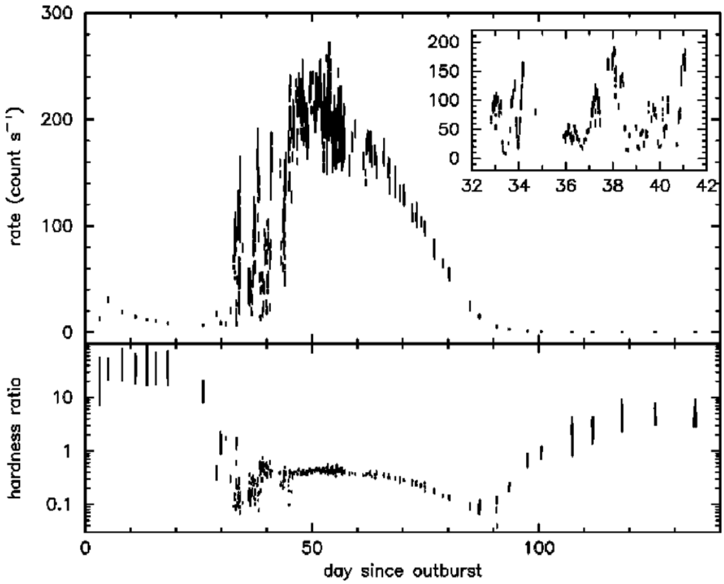


**Figure 2.** The *Swift* X-ray light-curve and hardness ratio of RS Oph. The inset shows a zoom-in of the changes in flux during the onset of the SSS phase.

## 3. High-Amplitude Flux Variability

One of the unexpected features of the RS Oph X-ray light-curve was the high-amplitude flux variability (sometimes more than an order of magnitude in 12 hours) seen at the beginning of the SSS phase (Figure 2). However, further monitoring campaigns of additional novae have shown this variability not to be unique to RS Oph. Figure 3 plots three other good examples: KT Eri (Beardmore *et al.* 2010), Nova LMC 2009a (Bode *et al.* in prep) and V458 Vul (Ness *et al.* 2009). In general, the X-ray emission is softer when brighter, but there are counter-examples (see Figure 4). The trend of being harder when fainter could be due to variable visibility of the WD surface. The hotter, optically thin emission seen in RS Oph spectra is approximately constant, and will contribute a larger fraction of the observed counts when the overall flux is low – that is, when there is less of the WD surface visible; thus, the emission would appear harder. Such variable

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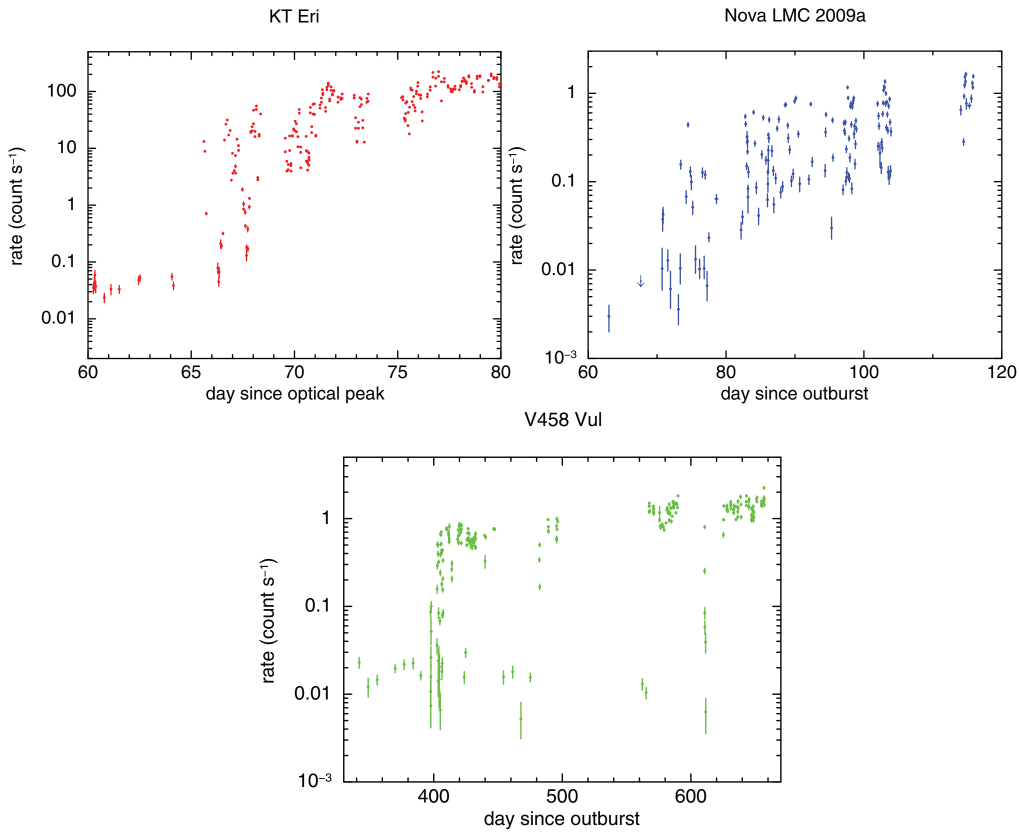


**Figure 3.** Examples of *Swift*-observed novae which show large variations in their X-ray count rates at the start of the SSS phase.

visibility could be caused by changing column density (either the amount of neutral absorbing material – i.e. 'clumpiness' – or a change in ionization state) or by a variation in the photospheric radius. Alternatively, a change in the photospheric temperature could also have an effect (see Osborne *et al.* 2011 for X-ray spectral fits throughout the nova outburst), with low temperatures leading to emission below the X-ray band, while higher temperatures increase the soft flux and, hence, decrease the hardness. An even higher temperature could lead to a rehardening, however, if some of the X-ray emission moves above the 2 keV limit used for the hardness ratio.

A spectrum from a time of peak count rate and one from the following trough were divided and the resulting ratio spectrum is shown in the right-hand panel of Figure 4. The ratio decreases both at the low- and high-energy ends, implying that the cause of the variation cannot be simply a change in column or radius. Investigating the proposed change in temperature shows that a similar spectral ratio could be produced, but it seems likely that a combination of effects is leading to the high-amplitude variations in the flux.

Of the novae in Figure 3, KT Eri and Nova LMC 2009a are both suspected RNe (as, of course, is RS Oph), while V458 Vul is a much slower system, as can be seen by the fact that the SSS was continuing at hundreds of days after outburst. Therefore, whatever it is which causes the large variations in flux, it is not likely to be directly related to the mass of the WD.

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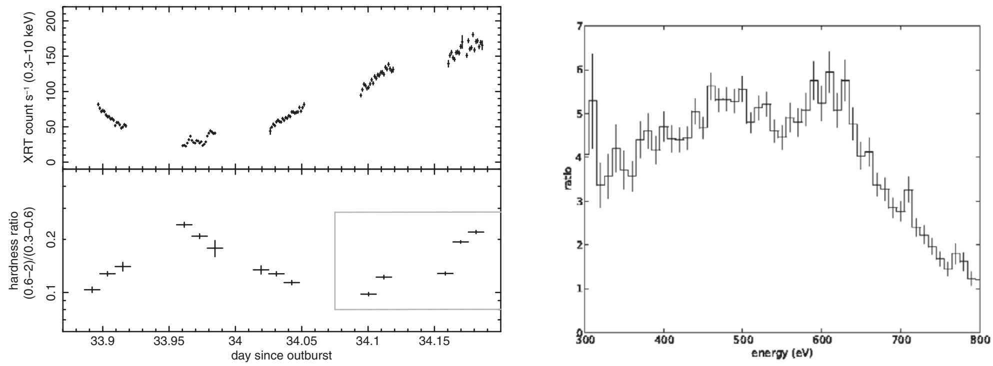


**Figure 4.** Left: A small section of the high-amplitude flux variability at the start of the SSS phase in RS Oph. The X-ray source was usually softer when brighter, but the grey box highlights exceptions. Right: A ratio spectrum, comparing the emission from a peak and trough during the variability. Both plots reproduced from Osborne *et al.* (2011).

Pre-*Swift*, some novae had revealed variability during the supersoft emission (e.g., V1491 Aql – Drake *et al.* 2003; V382 Vel – Orio *et al.* 2002; V4743 Sgr – Ness *et al.* 2003) which is yet to be explained, but it is uncertain whether these changes in flux have the same origin as the dramatic variability in the *Swift*-observed novae.

## 4. Quasi-Periodic Oscillations

Beside the large amplitude variability discussed in the previous section, the X-ray data obtained for RS Oph also demonstrated a 35s quasi-periodic oscillation (QPO). This oscillation was seen in *XMM-Newton* data (Ness *et al.* 2007) as well. The QPO was usually present when the source was brightest, though this was not always the case. Such an oscillation could be caused by the $\epsilon$-mechanism – a nuclear burning instability, whereby increased energy generation is followed by expansion, leading to a reduction in generation rate and hence a recontraction, which starts the cycle again. More details are given in Osborne *et al.* (2011).

Interestingly, KT Eri shows a period of $\sim$ 35s too (Beardmore *et al.* 2010). This reinforces the idea that the QPO is not related to rotation, since it is unlikely that two novae would have such similar periods. Since both objects are probably RNe, the similarity in this very short period (by far the shortest seen in the SSS phase of a nova to date) could suggest that both contain WDs close to the Chandrasekhar mass.

## 5. Turn-On and -Off Times of the SSS

Detailed monitoring campaigns, such as those performed by *Swift* for the brighter novae, help to identify the onset of the SSS and the subsequent rise to maximum. It is now known (see Section 3) that this is often chaotic, so dense sampling is very useful. Figure 6 shows four novae for which the start and stop of the SSS phase can be identified in *Swift* data. The turn-on times vary from around day 30 for RS Oph and V2491 Cyg, to several hundred days for V458 Vul. The SSS phase (generally corresponding to the peak flux in the X-rays) lasted only a few days for V2491 Cyg (Page *et al.* 2010), while V458 Vul showed supersoft emission for at least 700 days. The final three observations plotted for V458 Vul show a drop-off in count rate, though it is unclear whether this is

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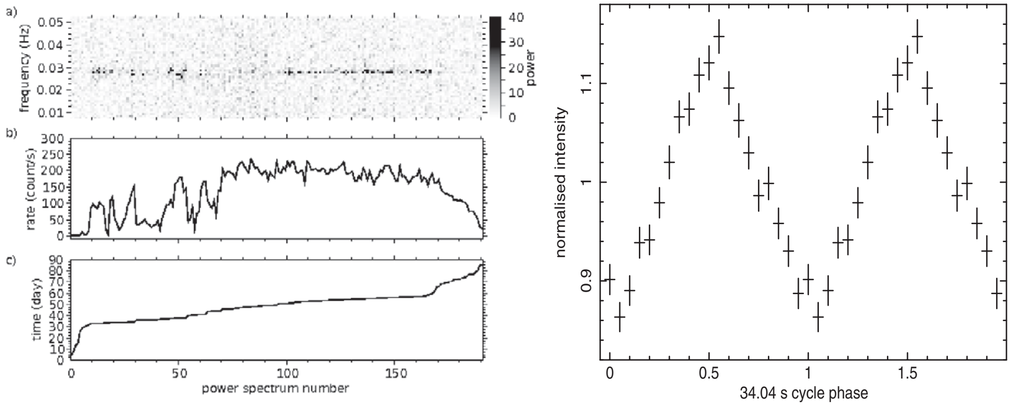


**Figure 5.** Left: The QPO seen in the soft X-ray flux of RS Oph, plotted against power spectrum number. a) Power spectra for successive observations. b) The source intensity for each power spectrum. c) The relationship between power spectrum number and time; this was done to suppress intervals were there were no observations. Right: A folded light-curve showing the QPO (varies between ~ 34 and ~ 36s). Plots reproduced from Osborne *et al.* (2011).

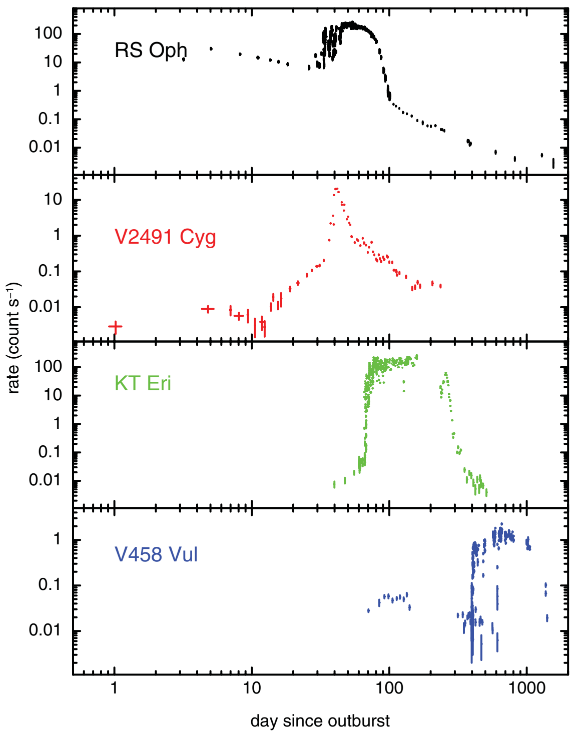


**Figure 6.** *Swift*-XRT light-curves showing both the turn-on and turn-off of the SSS emission.

actually the end of the SSS phase, or another temporary drop to very low flux as has been seen previously (days ~ 450, 560 and 610).

The turn-on time provides information about the matter ejected during the nova explosion. In general, a small amount of ejected mass should mean that the SSS phase starts earlier – less material needs to disperse in order for the WD surface to become visible – although a higher velocity of the ejecta would also speed up the process. Figure 7, taken

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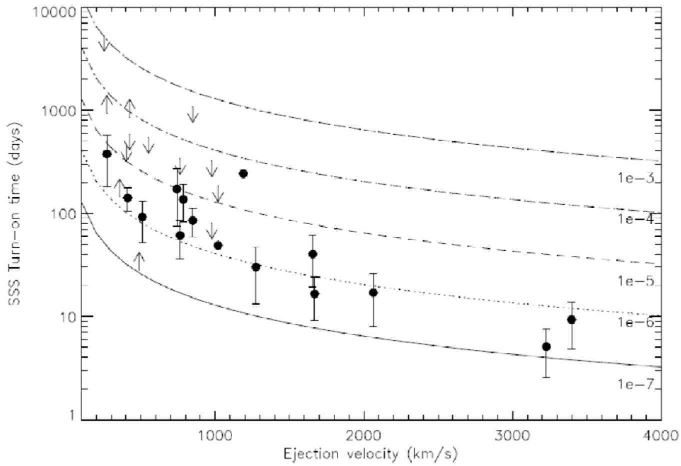


**Figure 7.** Relationship between the turn-on of the SSS and the ejection velocity for a sample of *Swift* novae. The lines plotted are from an equation given by Shore (2008) for different ejected masses (decreasing from top to bottom). Arrows indicate limits on the SSS time. This plot has been reproduced from Schwarz *et al.* (2011).

from Schwarz *et al.* (2011), plots the SSS turn-on times against the ejection velocity (which is given by FWHM/2.355, where FWHM is the width of the Balmer lines around the visual maximum). The lines shown are from a relation given by Shore (2008), with certain assumptions about the geometry, filling factor and column density. The fastest novae (i.e. those for which the SSS turns on most quickly, towards the bottom-right of the figure) must have ejected relatively small amounts of mass. As explained by Schwarz *et al.* (2011), this is consistent with independent estimates of the ejected mass.

The turn-off times of the SSS may also be informative, and in Figure 8 we consider two relationships which have been proposed in the literature. The left-hand panel shows the end time with respect to $t_2$, the time taken for the optical light-curve to decline by two magnitudes. Over-plotted is the relationship from Hachisu & Kato (2010), from which the end of nuclear burning is predicted using the break time of their model optical light-curves; the dotted lines are the uncertainties. The *Swift* results do not really confirm the model: although the overall trend is similar, there is a large amount of scatter in the *Swift* points, especially when the upper and lower limits are also accounted for. We do note that the Hachisu & Kato work used the $t_2$ from the $y$-band, however, while we have used the $V$-band data available from the AAVSO. The right-hand panel of Figure 8 plots the turn-off time against the FWHM velocity of H$\alpha$ or H$\beta$ near visual maximum. The dotted line is the relationship from Greiner, Orio & Schartel (2003), which was derived from only a small sample of novae. This larger sample from *Swift* does not really support the model; specifically, many of the slow novae have turned off more quickly than expected from the Greiner relation.

## 6. Optical Plateau

It has been noted that RNe often show a plateau in their visible light, which is speculated to arise from the reradiation of the SSS emission from an accretion disc (Hachisu *et al.* 2008) – though, oddly, the presence of the plateau does not appear to be affected by the system inclination, given that both RS Oph ($i = 39^o$) and U Sco ($i = 83^o$) show a plateau approximately coincident in time with their main SSS phases (Figure 9). KT Eri

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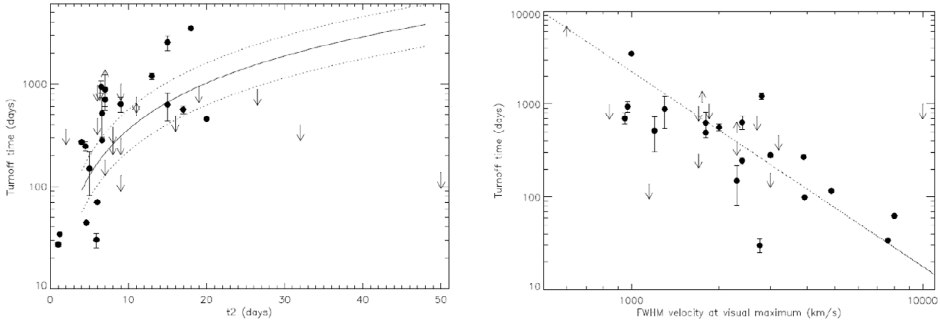


**Figure 8.** Left: Turn-off time against decline time for the optical light-curve, with the relationship proposed by Hachisu & Kato (2010). Right: Turn-off time against velocity at visual maximum, with the Greiner *et al.* (2003) relationship.

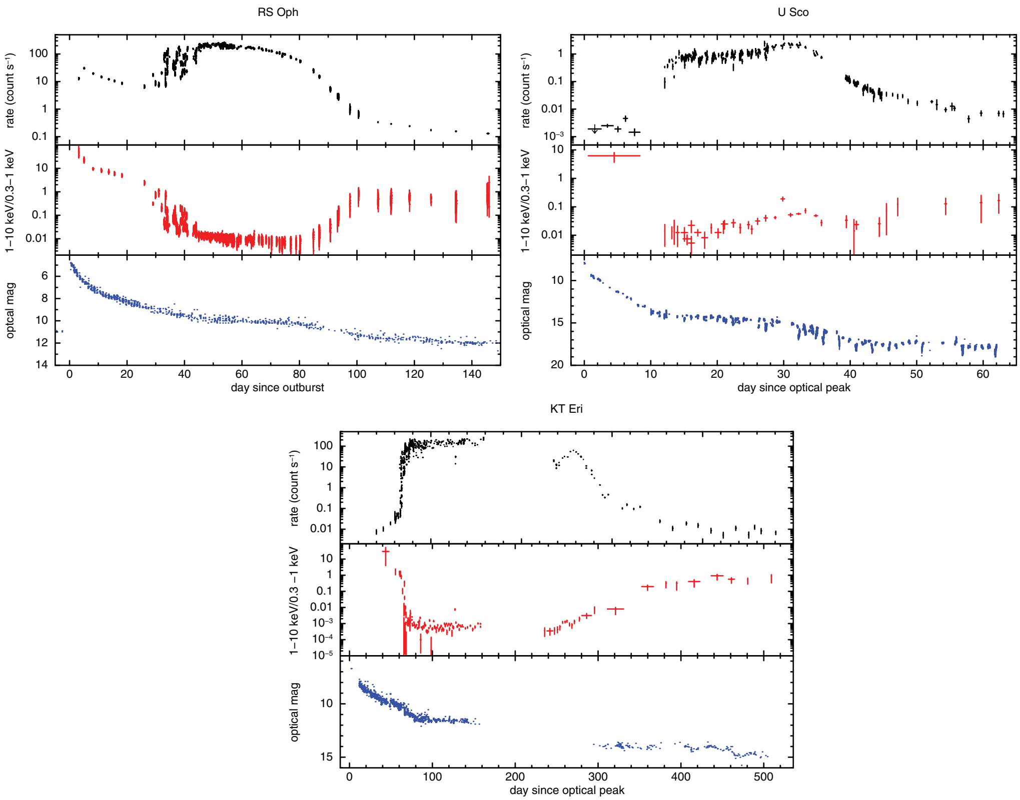


**Figure 9.** *Swift* X-ray light-curves, hardness ratios and optical light-curves (obtained from the American Association of Variable Star Observers) for three RNe which show plateau in their optical decays. These plateaux are approximately coincident in time with the brightest and softest X-ray emission.

appears to show a plateau, too, though the source went behind the Sun $\sim 160$ days after the optical peak, meaning that the end of the SSS (and, presumably, the plateau) was missed.

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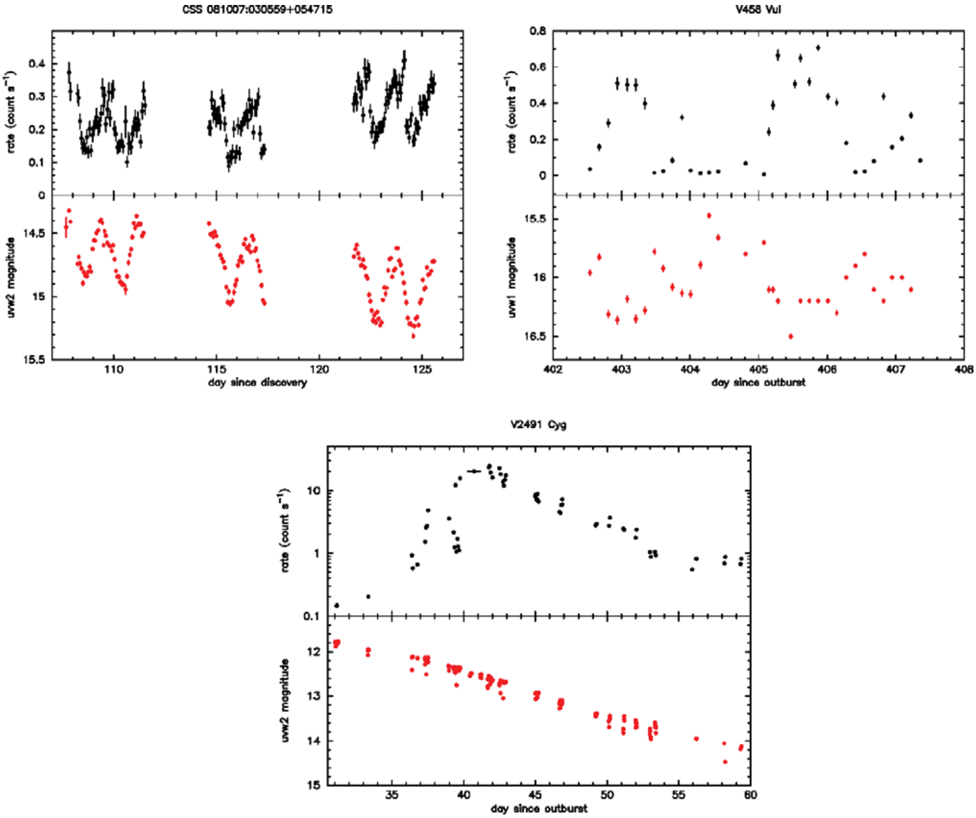


**Figure 10.** The X-ray and UV light-curves of three novae observed by *Swift* which demonstrate the similarities and differences between X-ray and UV variability.

## 7. X-ray and UV variability

Because *Swift* has the co-aligned XRT and UVOT, we usually obtain simultaneous X-ray and UV light-curves for the novae being monitored. In such cases it is interesting to compare the variability across these two bands, and, as Figure 10 shows, different novae can show very different patterns. CSS 081007:030559+054715 shows the X-ray and UV emission varying in phase, with a 1.77-day period (Beardmore *et al.* 2008), likely to be the orbital period of the system. As will be discussed in more detail by Beardmore *et al.* (in prep.), this may be caused by obscuration in a high-inclination system, as occurs in compact binary supersoft sources. Note that a single component responsible for the emission in both bands would lead to a very large luminosity. However, the UV emission may be produced through the reprocessing of the X-rays (Beardmore *et al.* in prep). In comparison, V458 Vul shows an approximate anti-phase correlation between the X-ray and UV bands (Drake *et al.* 2008), though this is not a one-to-one relationship. This could be caused by a temperature variation: as the mass accretion rate goes up, the WD photosphere expands, shifting the emission to the UV, and vice versa. V2491 Cyg (and, in fact, RS Oph) is an example where the UV emission just seems to fade away, while the X-rays vary up and down (see also Page *et al.* 2010). To summarize: different novae vary differently!

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## 8. Summary

Since its launch in 2004, *Swift* has observed a large number of novae, some with detailed monitoring campaigns, which have led to many interesting results, a few of which have been covered in this brief talk. All *Swift* data are immediately public and available from the Quick Look site (http://www.swift.ac.uk/access/ql.php) within a few hours of the observation, and then, after a week, from the archive (http://www.swift.ac.uk/swift_portal/archive.php). The UKSSDC also provides an online tool from which users can create spectra and light-curves for any object (http://www.swift.ac.uk/user_objects/).

### Acknowledgement

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