The rapid response capabilities of the Neil Gehrels Swift Observatory, together with the daily planning of its observing schedule, make it an ideal mission for following novae in the X-ray and UV bands, particularly during their early phases of rapid evolution and throughout the supersoft source interval. Many novae, both classical and recurrent, have been extensively monitored by Swift throughout their supersoft phase and later decline. We collect here results from observations of novae with outbursts which occurred between the start of 2006 and the end of 2017.

Keywords: novae, cataclysmic variables; ultraviolet: stars; X-rays: stars

1. Introduction

A nova occurs in a binary system, consisting of a white dwarf (WD) and a late-type main sequence or giant secondary star, when sufficient hydrogen is transferred from the secondary to the WD surface such that the temperature and pressure are high enough to ignite the material, leading to a thermonuclear runaway. After the initial explosion (which will appear as a new optical
source), the ejected envelope spreads out, becoming optically thin; at this stage, the surface nuclear burning becomes visible (assuming it is still ongoing). This emission peaks in the soft X-ray band, and is therefore known as the Supersoft Source (SSS) phase.

Besides this soft emission, novae also often show faint, hard (∼1–10 keV) X-rays (e.g., Brecher et al., 1977; Orio et al., 2001; Mukai et al., 2008; Chomiuk et al., 2014b), caused by ejecta shocks; this harder emission may be detectable before, during and after the SSS phase. More recently, novae have also been detected in the GeV γ-ray range by the Fermi-Large Area Telescope (LAT; Atwood et al., 2009, see Section 4 for more discussion).

2. Setting the scene

Before the launch of the Swift Gamma-Ray Burst Explorer Mission¹ (Gehrels et al., 2004), only a small number of novae had been detected in the X-ray band. Nova Cyg 1992 (V1974 Cyg) was the most well monitored of these sources, with 18 ROSAT-PSPC observations collected (Krautter et al., 1996).

As the left-hand panel of Fig. 1 shows, the nova was found to brighten, becoming a super-soft source and plateauing in X-rays for a few hundred days, before fading away rapidly. The shape of the light-curve was explained as the unveiling of the X-ray source as the ejecta cleared, with the source turning off as nuclear burning ceased (Krautter et al., 1996).

Around a decade after these observations, on 2004 November 20, Swift was launched: a mission designed to detect and follow-up Gamma-Ray Bursts (GRBs), but also very well-suited to monitor transient sources such as novae. In 2006 February, the recurrent nova RS Oph went into outburst. Thanks to the daily planning of Swift observing schedules, monitoring of the nova began within three days of the outburst; the most recent data point was actually collected in 2014 May, more than 3000 days later. Fig. 1 (right-hand panel) plots the X-ray data collected, demonstrating that, while the underlying shape is similar to V1974 Cyg - an underlying rise, plateau and fall is visible - the detailed monitoring revealed deviations from the relatively smooth time-series seen in the earlier nova. In particular, the rise to peak count rate was

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¹In 2018 the satellite was renamed the Neil Gehrels Swift Observatory in honour of the former Principal Investigator: https://www.nasa.gov/feature/goddard/2018/nasas-newly-renamed-swift-mission-spies-a-comet-slowdown
Figure 1: Left: *ROSAT* light-curve (0.1–2.4 keV) of V1974 Cyg (taken from Krautter et al., 1996), demonstrating the most detailed X-ray light-curve of a nova obtained before the launch of *Swift*. Right: The X-ray light-curve (0.3–10 keV) of RS Oph (Osborne et al., 2011a) obtained from the first detailed *Swift* monitoring campaign of a nova. Only the first 150 days after outburst are shown.

not at all monotonic, but rather showed high amplitude variability – an order of magnitude or more in about 12 hours.

This high-cadence monitoring campaign of RS Oph (details published by Bode et al., 2006c; Osborne et al., 2011a; Vaytet et al., 2011, for example) clearly highlighted the abilities of *Swift* in this field, inspiring many more observations of novae by the mission.

A number of *Swift* nova synopsis papers have been compiled over the years (Ness et al., 2007a; Schwarz et al., 2011; Osborne, 2015). In this article we add to these results, presenting the most complete sample of *Swift*-monitored novae to date, concentrating mainly on the SSS emission.

3. *Swift* observations of supersoft novae

Between 2006 and the end of 2017, *Swift* detected 30 novae in either our Galaxy or the Magellanic Clouds\(^2\) with SSS emission. In addition, more than 50 other Galactic novae were observed but not detected in the X-ray band, or only showed hard emission; we do not include these objects in this paper. We have, however, included V2362 Cyg and V1534 Sco in this current sample despite there being no obvious detection of SSS emission in these datasets, because a substantial amount of *Swift* data was collected. Observations of

\(^{2}\)We do not consider the many M31 novae here.
V2362 Cyg did not begin for almost 200 days after outburst, while in the case of V1534 Sco, the softening of the spectrum can be modelled by a decrease in the absorbing column which remains relatively high ($10^{23-21} \text{cm}^{-2}$) throughout the observations (Page et al., 2014e).

Of these 32 novae, most were monitored with both the X-ray Telescope (XRT; Burrows et al., 2005) and the UV/Optical Telescope (UVOT; Roming et al., 2005), though in some cases the UV source was too bright for conventional photometry. Table 1 lists these novae, together with their outburst times from the literature. For confirmed recurrent novae, marked with an asterix, only the most recent outburst date (i.e., that observed by Swift) is listed. V959 Mon was discovered as a new GeV source by LAT at a time when that area of the sky was too close to the Sun for ground-based (or Swift) observations; the optical nova was confirmed some seven weeks later (Cheung et al., 2012; Fujikawa et al., 2012). Nova SMC 2012 was announced four months after the actual outburst, when a new transient detection system was implemented by OGLE (Optical Gravitational Lensing Experiment; Wyrzykowski et al., 2012).

Figures 2–13 show the Swift results for these novae. In each case, the top panel shows the XRT light-curve over 0.3–10 keV, while the X-ray hardness ratio is plotted in the second panel, here defined as hard-band counts divided by soft-band counts. The precise cut between the soft and hard bands has been chosen on a case-by-case basis, depending on the shape of the X-ray spectrum. In most cases this cut is taken to separate the SSS emission from the harder (shock) component. However, for some novae the only emission clearly detected is soft (i.e. the vast majority of counts lie below about 1 keV); in these cases (HV Cet, V339 Del, V407 Lup and Nova SMC 2016), the hardness ratio compares two bands within the soft emission. When standard UVOT photometry could be utilised, a third panel shows the magnitude light-curve in whichever filters were predominantly used. In the cases of KT Eri and V5668 Sgr, all the UVOT observations were obtained using the grism; the panel therefore shows flux estimated from the grism spectra. In order to display the main emission intervals more clearly, occasionally early or late data points have been excluded from the plots.

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3 with the exception of V5855 Sgr, since there was only a single (soft) X-ray detection obtained for this source
Table 1: Outburst information from the literature for the novae presented in this paper. The last column gives the reference for the date of outburst. * Recurrent nova. Date is most recent outburst. 1 While the optical nova was discovered on 2012-08-09.8061, the \( \gamma \)-ray source was found almost 2 months earlier. 2 Outburst occurred between 2012-02-24 and 2012-06-05.

| Nova         | Alternative names | Date of outburst UT | Reference                     |
|--------------|-------------------|---------------------|-------------------------------|
| RS Oph*      | —                 | 2006-02-12.8        | Narumi et al. (2006)          |
| V2362 Cyg    | Nova Cyg 2006     | 2006-04-02.807      | Nakano et al. (2006)          |
| V1280 Sco    | Nova Sco 2007     | 2007-02-04.8624     | Yamaoka et al. (2007a)        |
| V1281 Sco    | Nova Sco 2007 No. 2 | 2007-02-19.8593    | Yamaoka et al. (2007b)        |
| V458 Vul     | Nova Vul 2007     | 2007-08-08.54       | Nakano et al. (2007)          |
| V598 Pup     | XMMSL1 J070542.7-381442 | 2007-10-09       | Read et al. (2007, 2008)      |
| V597 Pup     | Nova Pup 2007     | 2007-11-14.23       | Pereira et al. (2007)         |
| V2468 Cyg    | Nova Cyg 2008a    | 2008-03-07.801      | Nakano et al. (2008a)         |
| V2491 Cyg    | Nova Cyg 2008 No. 2 | 2008-04-10.728     | Nakano et al. (2008b)         |
| HV Cet       | CSS 081007:030559+054715 | 2008-10-07.381    | Beardmore et al. (2012)       |
| Nova LMC 2009a* | Nova LMC 1971b   | 2009-02-05.067      | Liller (2009)                 |
| V1213 Cen    | Nova Cen 2009     | 2009-05-08.235      | Pojmanski et al. (2009)       |
| V2672 Oph    | Nova Oph 2009     | 2009-08-16.515      | Nakano et al. (2009)          |
| KT Eri       | Nova Eri 2009     | 2009-11-14.632      | Yamaoka et al. (2009)         |
| U Sco*       | —                 | 2010-01-28.4385     | Schaefer et al. (2010)        |
| V407 Cyg     | —                 | 2010-03-10.797      | Nishiyama & Kabashima (2010)  |
| T Pyx*       | —                 | 2011-04-14.2391     | Waagen et al. (2011)          |
| Nova LMC 2012 | TCP J04550000-7027150 | 2012-03-26.397    | Seach (2012)                  |
| V5589 Sgr    | Nova Sgr 2012; PNV J17452791-2305213 | 2012-04-21.011 | Korotkiy et al. (2012)        |
| V959 Mon     | Nova Mon 2012; PNV J06393874+0553520 | 2012-06-22        | Fujikawa et al. (2012) Cheung et al. (2012) |
| Nova SMC 2012 | OGLE-2012-NOVA-002 | 2012-06-05         | Wyrzykowski et al. (2012)     |
| V339 Del     | Nova Del 2013; PNV J20233073+2046041 | 2013-08-14.584    | Nakano (2013)                 |
| V1369 Cen    | Nova Cen 2013; PNV J13544700-5909080 | 2013-12-02.692    | Seach (2013)                  |
| V745 Sco*    | —                 | 2014-02-06.694      | Waagen & Pearce (2014)        |
| V1534 Sco    | Nova Sco 2014; TCP J17154683-3128303 | 2014-03-26.84867 | Nishiyama & Kabashima (2014) |
| V1535 Sco    | Nova Sco 2015; PNV J17032620-3504140 | 2015-02-11.8367   | Nakano (2015)                 |
| V5668 Sgr    | Nova Sgr 2015 No. 2; PNV J18365700-2855420 | 2015-03-15.634 | Seach (2015)                  |
| Nova LMC 1968-12a* | OGLE-2016-NOVA-01 | 2016-01-21.2094    | Mroz & Udalski (2016a)        |
| V407 Lup     | Nova Lup 2016; ASASSN-16kt | 2016-09-24.00    | Stanek et al. (2016)          |
| Nova SMC 2016 | —                 | 2016-10-09-09.2     | Mroz & Udalski (2016b)        |
| V5855 Sgr    | Nova Sgr 2016 No. 3; TCP J18102829-2729590 | 2016-10-20.383 | Nakano et al. (2016)          |
| V549 Vel     | Nova Vel 2017; ASASSN-17mt | 2017-09-24.39    | Stanek et al. (2017)          |
Figure 2: Novae from 2006. The hardness ratio bands vary between different novae, as explained in the text.
Figure 3: Novae from 2007. The hardness ratio bands vary between different novae, as explained in the text. Note that the light-curve of V598 Pup only covers a short time interval, and is therefore plotted on a linear time axis.
Figure 3: Novae from 2007 – continued from previous page

V1281 Sco

V458 Vul
Figure 3: Novae from 2007 – continued from previous page

![Graphs of V598 Pup and V597 Pup showing UV magnitudes and rates over time.]
Figure 4: Novae from 2008. The hardness ratio bands vary between different novae, as explained in the text.
Figure 4: Novae from 2008 – continued from previous page
Figure 5: Novae from 2009. The hardness ratio bands vary between different novae, as explained in the text.
Figure 5: Novae from 2009 – continued from previous page
Figure 6: Novae from 2010. The hardness ratio bands vary between different novae, as explained in the text.
Figure 7: Nova from 2011. The hardness ratio bands vary between different novae, as explained in the text.
Figure 8: Novae from 2012. The hardness ratio bands vary between different novae, as explained in the text.
Figure 8: Novae from 2012 – continued from previous page
Figure 9: Novae from 2013. The hardness ratio bands vary between different novae, as explained in the text.
Figure 10: Novae from 2014. The hardness ratio bands vary between different novae, as explained in the text.
Figure 11: Novae from 2015. The hardness ratio bands vary between different novae, as explained in the text.
Figure 12: Novae from 2016. The hardness ratio bands vary between different novae, as explained in the text.
Table 2 lists the *Swift* timings for the novae: the range of first to last observations taken, the first X-ray detection (hard or soft) and the first detection of supersoft emission. In the instances where the observations cover an extended period, there were long gaps between the later snapshots of data. For a couple of the novae (marked in the table), there were also long gaps between the initial and subsequent observations.
Figure 13: Nova from 2017. The hardness ratio bands vary between different novae, as explained in the text.
Table 2: Swift results for the novae presented in this paper. ¹No observations taken between days 5.3 and 822.5, or between 928.1 and 2285.8. ²No observations between days 1.9 and 337.7. ³No observations between days 14.6 and 323.0.

| Nova       | Interval of Swift obs. (day after outburst) | First XRT detection (day after outburst) | First SSS detection (day after outburst) | References                      |
|------------|---------------------------------------------|------------------------------------------|------------------------------------------|----------------------------------|
| RS Oph     | 3.2–3046.9                                   | 3.2                                      | 26.0                                     | Osborne et al. (2006a,b,c,d)     |
|            |                                             |                                          |                                          | Bode et al. (2006a,b,c)          |
|            |                                             |                                          |                                          | Osborne et al. (2011a)            |
| V2362 Cyg  | 194.3–820.7                                  | 194.3                                    | —                                        | Lynch et al. (2008)               |
| V1280 Sco  | 5.3–4401.1¹                                 | 822.5                                    | 2285.8                                   | Osborne et al. (2007)            |
|            |                                             |                                          |                                          | Ness et al. (2009a)               |
| V1281 Sco  | 1.9–819.0²                                  | 337.7                                    | 337.7                                    | Osborne et al. (2007)            |
|            |                                             |                                          |                                          | Ness et al. (2008a)               |
| V458 Vul   | 1.1–1487.9                                   | 70.5                                     | 397.6                                    | Drake et al. (2007)              |
|            |                                             |                                          |                                          | Drake et al. (2008a)             |
|            |                                             |                                          |                                          | Drake et al. (2008b)             |
|            |                                             |                                          |                                          | Ness et al. (2009b)              |
| V598 Pup   | 168.8–255.8                                  | 168.8                                    | 168.8                                    | Read et al. (2008)               |
|            |                                             |                                          |                                          | Page et al. (2009)               |
| V597 Pup   | 6.1–584.6                                    | 55.0                                     | 120.3                                    | Ness et al. (2008b)              |
| V2468 Cyg  | 458.4–2311.6                                 | 458.4                                    | 1266.7                                   | Schwarz et al. (2009a)           |
|            |                                             |                                          |                                          | Schwarz et al. (2009b)           |
| Nova             | Interval of *Swift* obs. (day after outburst) | First XRT detection (day after outburst) | First SSS detection (day after outburst) | References                                      |
|------------------|------------------------------------------------|------------------------------------------|-------------------------------------------|------------------------------------------------|
| V2491 Cyg        | 1.0–236.0                                       | 1.0                                      | 33.3                                      | Page et al. (2012b)                             |
|                  |                                                |                                          |                                           | Ibarra & Kuulkers (2008)                       |
|                  |                                                |                                          |                                           | Ibarra et al. (2008)                           |
|                  |                                                |                                          |                                           | Kuulkers et al. (2008)                         |
|                  |                                                |                                          |                                           | Page et al. (2008, 2010)                       |
|                  |                                                |                                          |                                           | Osborne et al. (2008)                          |
|                  |                                                |                                          |                                           | Ibarra et al. (2009)                           |
|                  |                                                |                                          |                                           | Ness et al. (2011)                             |
|                  |                                                |                                          |                                           | Takei et al. (2011)                            |
| HV Cet           | 34.1–299.6                                      | 34.1                                    | 34.1                                      | Schwarz et al. (2008)                          |
|                  |                                                |                                          |                                           | Beardmore et al. (2008a, 2012)                 |
|                  |                                                |                                          |                                           | Osborne et al. (2009)                          |
| Nova LMC 2009a   | 9.2–382.3                                       | 63.0                                    | 70.7                                      | Bode et al. (2009a,b, 2016)                    |
| V1213 Cen        | 14.6–1407.1<sup>a</sup>                         | 323.0                                   | 323.0                                     | Schwarz et al. (2010)                          |
| V2672 Oph        | 1.5–72.5                                        | 1.5                                     | 14.7                                      | Schwarz et al. (2009c)                         |
|                  |                                                |                                          |                                           | Takei et al. (2014)                            |
| KT Eri           | 13.1–734.3                                      | 39.9                                    | 55.5                                      | Bode et al. (2010, 2016)                       |
|                  |                                                |                                          |                                           | Beardmore et al. (2010)                        |
| U Sco            | 0.6–63.1                                        | 2.6                                     | 12.1                                      | Schlegel et al. (2010a,b)                      |
|                  |                                                |                                          |                                           | Osborne et al. (2010)                          |
|                  |                                                |                                          |                                           | Pagnotta et al. (2015)                         |
|                  |                                                |                                          |                                           | Takei et al. (2013)                            |

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Table 2 – continued from previous page

| Nova          | Interval of *Swift* obs. (day after outburst) | First XRT detection (day after outburst) | First SSS detection (day after outburst) | References                                      |
|---------------|-----------------------------------------------|-----------------------------------------|------------------------------------------|------------------------------------------------|
| V407 Cyg      | 3.0–1228.1                                    | 3.0                                     | 12.4                                     | Shore et al. (2011) Nelson et al. (2012a)       |
| T Pyx         | 0.31–718.9                                    | 0.31                                    | 122.8                                    | Kuulkers et al. (2011) Osborne et al. (2011b) Tofflemire et al. (2013) Chomiuk et al. (2014a) |
| Nova LMC 2012 | 1.3–671.0                                     | 18.1                                    | 18.1                                     | Page et al. (2012a) Schwarz et al. (2015)       |
| V5589 Sgr     | 0.9–108.4                                     | 19.7                                    | 64.6                                     | Sokolovsky et al. (2012) Nelson et al. (2012b) Weston et al. (2016b) |
| V959 Mon      | 58.5–1002.8                                   | 58.5                                    | 149.7                                    | Nelson et al. (2012c,d) Osborne et al. (2013a) Page et al. (2013a,f) |
| Nova SMC 2012 | 135.8–439.0                                   | 135.8                                   | 270.4                                    | Schwarz et al. (2012) Page et al. (2013b,c)     |
| V339 Del      | 0.4–408.0                                     | 35.6                                    | 59.7                                     | Kuulkers et al. (2013a) Nelson et al. (2013) Page et al. (2013d,e, 2014d) Page & Beardmore (2013) Osborne et al. (2013b) Beardmore et al. (2013) |

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| Nova          | Interval of *Swift* obs. (day after outburst) | First XRT detection (day after outburst) | First SSS detection (day after outburst) | References                           |
|--------------|-----------------------------------------------|----------------------------------------|---------------------------------------|-------------------------------------|
| V1369 Cen    | 1.2–1967.3                                     | 78.0                                   | 128.2                                 | Shore et al. (2016)                 |
|              |                                                |                                        |                                       | Kuulkers et al. (2013b)             |
|              |                                                |                                        |                                       | Page et al. (2014c)                 |
|              |                                                |                                        |                                       | Mason et al. (2018)                 |
| V745 Sco     | 0.2–229.2                                      | 0.2                                    | 3.4                                   | Mukai et al. (2014)                 |
|              |                                                |                                        |                                       | Page et al. (2014a,b, 2015d)        |
|              |                                                |                                        |                                       | Beardmore et al. (2014)             |
| V1534 Sco    | 0.3–85.5                                       | 0.3                                    | —                                     | Kuulkers et al. (2014)             |
|              |                                                |                                        |                                       | Page et al. (2014e)                 |
| V1535 Sco    | 3.9–80.4                                       | 3.9                                    | 11.7                                  | Nelson et al. (2015)               |
|              |                                                |                                        |                                       | Linford et al. (2017)               |
| V5668 Sgr    | 2.6–848.2                                      | 95.3                                   | 167.9                                 | Page et al. (2015a,b,c)             |
|              |                                                |                                        |                                       | Gehrz et al. (2018)                |
| Nova LMC 1968-12a | 2.1–85.9                                    | 2.1                                    | 6.4                                   | Darnley et al. (2016)              |
|              |                                                |                                        |                                       | Page et al. (2016a)                |
|              |                                                |                                        |                                       | Kuin et al. in prep.               |
| V407 Lup     | 2.9–683.7                                      | 150.1                                  | 150.1                                 | Beardmore et al. (2017a)            |
|              |                                                |                                        |                                       | Orio et al. (2017)                 |
|              |                                                |                                        |                                       | Beardmore et al. (2017b)            |
|              |                                                |                                        |                                       | Aydi et al. (2018b)                |
| Nova SMC 2016| 5.5–318.7                                      | 28.2                                   | 28.2                                  | Kuin et al. (2016)                 |
|              |                                                |                                        |                                       | Page et al. (2016b)                |

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Table 2 – continued from previous page

| Nova          | Interval of *Swift* obs. (day after outburst) | First XRT detection (day after outburst) | First SSS detection (day after outburst) | References        |
|---------------|---------------------------------------------|------------------------------------------|------------------------------------------|-------------------|
| V5855 Sgr     | 7.6–129.9                                   | 129.9                                    | 129.9                                    | Aydi et al. (2018a) |
| V549 Vel      | 52.5–407.4                                  | 52.5                                     | 233.8                                    | Nelson et al. (2019) |
|               |                                             |                                          |                                          | Page et al. (2018)  |
3.1. Highlights of Swift results

*Swift* observations of SSS emission from novae have discovered a number of unexpected and interesting features, which are briefly discussed below.

### 3.1.1. High-amplitude flux variability

Observations of RS Oph first identified that the initial rise to peak soft X-ray emission was chaotic. The X-ray count rate was found to vary significantly, sometimes by more than an order of magnitude in 12 hours (Figs. 1 and 2), before settling at a consistently high count rate for around 20 days, and then fading rapidly away. The emission is typically softer when brighter, both on long and short timescale, though, as discussed in Osborne et al. (2011b), occasional counter-examples were found. Monitoring campaigns since RS Oph have shown this high-amplitude flux variability not to be unique to that source, with other novae showing a similar phenomenon (e.g., KT Eri, Nova LMC 2009a, V2491 Cyg, V458 Vul; see references in Table 2). However, not all novae followed in detail show this variability: V745 Sco (Page et al., 2015d) is a prime example of a smooth rise to peak SSS emission.

As has been previously discussed (e.g., Page, 2013; Schwarz et al., 2011; Osborne et al., 2011a), these large scale changes in flux are at least partly due to variable visibility of the hot WD. Following a nova explosion, material will be expelled from the WD surface. If these clumpy ejecta pass through the observer’s line of sight, then the count rate will drop as the X-rays are absorbed. Fits to the SSS X-ray spectra also reveal variations in the photospheric temperature (e.g., Page & Osborne, 2014; Osborne et al., 2011a), where a lower temperature (below $\sim 30$ eV) can lead to part, if not most, of the SSS emission being below the XRT bandpass, thus decreasing the measured count rate.

### 3.1.2. Quasi-periodic oscillations

Continuing its surprises, RS Oph X-ray data also demonstrated a 35s quasi-periodic oscillation (QPO; Osborne et al., 2011b, 2006b; Beardmore et al., 2008b); this periodicity was confirmed in *XMM-Newton* data by Ness et al. (2007b). Subsequently QPOs were also identified in other bright, supersoft novae, for example KT Eri (Beardmore et al., 2010), V339 Del (Beardmore et al., 2013), V745 Sco (Beardmore et al., 2014) and V5668 Sgr (Page et al., 2015c). The persistent SSS Cal 83 also shows a similar periodicity (Odendaal et al., 2014; Ness et al., 2015b). Ness et al. (2015b) is a summary paper of
QPO results found in *XMM-Newton* and *Chandra* light-curves, while the *Swift* data will be published in Beardmore et al. (in prep.).

### 3.1.3. X-ray and UV variability

During the evolution of a nova, nuclear burning is expected to continue at constant bolometric luminosity during the phase of stable shell burning (e.g. Gallagher & Starrfield, 1976; Macdonald, Fujimoto & Truran, 1985), with the spectral energy distribution shifting to higher energies as the outburst progresses. Such a phase is not always obvious from observational data, though. Page et al. (2010) analysed the *Swift* X-ray spectra of V2491 Cyg, finding no obvious evidence for a constant bolometric luminosity phase. Likewise, Page et al. (2015d) investigated the apparent lack of the phase in V745 Sco; forcing the bolometric luminosity of the soft component model to remain constant, the photospheric radius would need to decrease by a factor of $\sim 30$ over this interval. However, Aydi et al. (2018a,b) found that the bolometric luminosity appeared close to constant for 100–150 day in both Nova SMC 2016 and V407 Lup, and RS Oph showed a plateau in luminosity for a few tens of days (Osborne et al., 2011a).

While some of the X-ray light-curves presented here do show plateau phases during the SSS emission, others are far from constant. The X-ray count rate is certainly not a precise proxy for the bolometric luminosity – variations in spectral shape and absorption will alter the count rate to luminosity conversion. In addition, the bolometric correction can be quite uncertain for low temperatures peaking towards the lower energy bound of the XRT bandpass. In summary, the presence of a constant bolometric luminosity phase is not always clear in *Swift*-XRT observations.

As demonstrated in Figs. 2–13, *Swift* data are usually obtained simultaneously with both the XRT and UVOT. Comparison of the variability across these two bands shows different patterns for different novae. HV Cet (Fig. 4) is an example where the X-ray and UV emission is modulated in phase, with a 1.77-day period. As discussed in Beardmore et al. (2012) and Osborne (2015), this is thought to be caused by obscuration in a high-inclination system. In the case of HV Cet, it is believed that the WD itself is permanently hidden by a scattering region, and that the X-rays detected have been scattered into our line of sight, also explaining the sub-Eddington luminosities measured. The UV is then formed through reprocessed X-rays, with the emission occulted by the disc rim each 1.77 day orbit. Ness et al. (2013) present a study of SSS grating spectra, finding two distinct types: those
dominated by absorption lines (termed SSa) and those where emission lines are most prominent (SSe). They interpret the SSe systems as those where the central source is obscured, and HV Cet is classified as an SSe source, supporting the description above.

In contrast, for V458 Vul (Fig. 3; Ness et al., 2009b; Schwarz et al., 2011) there is an approximate anti-correlation between the X-ray and UV data, similar to the results found for persistent SSS, such as RX J0513.9–6951 (Reinsch et al., 2000), where the variability is speculated to be caused by changes in the mass accretion rate. As the accretion rate onto the WD increases, its photosphere expands and cools, shifting the peak of the emission into the extreme UV; when the photosphere shrinks back down, the X-rays would become stronger again.

Finally, there are situations where there is no discernible correlation between the X-ray and UV photons. In the cases of V2491 Cyg and V745 Sco (Figs. 4 and 10; Page et al., 2010; Ness et al., 2011; Page et al., 2015d), for example, the X-rays brighten, peak and decay, while the UV simply fades over time. V5668 Sgr (Fig. 11; Gehrz et al., 2018) shows an example of a dust dip and recovery in the UV band which is not observed in the X-ray band. Such examples suggest the X-ray and UV emitting regions are distinct in these novae.

It has previously been noted that recurrent novae often show a plateau in their optical light-curves coincident in time with the SSS phase (Hachisu et al., 2006, and references therein), which is speculated to arise from the re-radiation of the bright SSS emission from an accretion disc. Such flattenings can also sometimes be seen in UV light-curves, with KT Eri and U Sco (Figs. 5 and 6) being good examples in the current Swift sample.

Periodic variations in the UVOT data have been used to identify orbital periods in some novae (for example, Beardmore et al., 2012; Aydi et al., 2018b; Bode et al., 2016). Given its orbit of ~ 1.5 hr, Swift can measure timescales close to a day which are generally difficult to do from the ground. However, the detection of intermediate polar (IP)-like spin periods (~ 300–1000 s) is more difficult with Swift data, given its observing strategy (continuous snapshots of data typically being shorter than ~ 1.8 ks) and the corresponding effect on the light-curve window function.

3.1.4. SSS turn-on and turn-off times

The turn-on and turn-off times of the SSS emission (and, hence, nuclear burning) can provide useful information about the WD parameters. With
the high cadence monitoring regularly performed by Swift, tying down these times more accurately becomes significantly easier.

For example, visibility of the supersoft emission requires that the nova ejecta are optically thin to X-rays. Therefore, the turn-on time of the SSS phase (together with the expansion velocity) tells us about the mass of the ejected shell. Schwarz et al. (2011) reviewed a sample of Swift-observed novae with supersoft emission, clearly demonstrating how the novae with faster velocities and an earlier SSS turn-on are consistent with lower ejected masses (Shore, 2008). Their results also show that recurrent novae tend to be located at the high-velocity/early-SSS/low-ejecta locus of the diagram, as expected for higher-mass WDs.

Knowing the start/stop times of the SSS emission and, therefore, the duration of the nuclear burning interval, can also provide an estimate of the mass ejected (Shara et al., 2010).

4. Open questions

Osborne (2015) presented a review of nova observations obtained by Swift before 2015 April, including a list of open questions. Despite the four years which have passed since that work was published, to some extent the same areas for future work still remain. For completeness, we summarise and update these points below.

- This paper has concentrated mainly on temporal information obtained from Swift observations. There are, of course, corresponding spectra obtained throughout the evolution of the novae. The problem which then arises is how to model these SSS data. While, at first glance, the spectra look decidedly blackbody-like, sometimes with superimposed absorption edges, from a physical standpoint this is not valid. Krautter et al. (1996) first pointed out that parameterising the SSS spectra with blackbodies tends to underestimate the photospheric temperature, and overestimate the luminosity (although this does not always seem to be the case; Osborne et al., 2011b). High-resolution grating data, from XMM-Newton or Chandra, reveal complex spectra (e.g., Ness et al., 2007b) for which stellar atmosphere models are clearly required, and Page & Osborne (2014) presented a preliminary investigation of Swift spectra fitted with atmosphere grids. The resolution of CCD spectra such as those from Swift-XRT is not typically high enough to constrain
fully the parameters needed for such models. However, even when considering grating spectra, the atmosphere models available at the present time are not sufficiently advanced to parameterise the data accurately, and should be regarded as a work in progress.

- While QPOs have been detected in *Swift* light-curves since 2006, our understanding of what causes them remains incomplete. Periodicities ranging from $\sim 35$–$70$ s have been seen in *Swift*-XRT data during the SSS phase, in RS Oph (Osborne et al., 2006b; Beardmore et al., 2008b; Osborne et al., 2011a), KT Eri (Beardmore et al., 2010), V339 Del (Beardmore et al., 2013) and V5668 Sgr (Page et al., 2015c; Gehrz et al., 2018). Possible explanations for these oscillations include pulsations or rotation of the WD. However, recent pulsation stability analysis suggests that those longer than 10–20 s for a high-mass system like RS Oph would be quickly damped (Wolf et al., 2018). Considering rotation, periods under 100 s are not uncommon in cataclysmic variables (e.g., Ritter & Kolb, 2003). However, assuming SSS emission originates from an extended nuclear-burning atmosphere, asymmetries would be required to produce modulations. In the case of magnetic WDs, hot spots could be caused by material funnelling into the poles, enhancing the nuclear burning in these regions; indeed, Aydi et al. (2018b) proposed that V407 Lup was a new IP nova system. Work to be included in a paper by Beardmore et al. finds that RS Oph XRT data extracted during the intervals of the 35 s QPO show the spectrum to be harder at the time of the modulation maximum, which can be explained by variations in the oxygen column density. A similar change in column density was noted by Ness (2015a) when exploring longer timescale variations found in *Chandra* data.

- The link – if any – between the shock (non-SSS) emission in the XRT band and the *Fermi*-LAT detections deserves further investigation. At the time of writing, 14 novae have been announced as having a GeV detection by the *Fermi* Large Area Telescope (LAT); of these, nine are included in the *Swift* sample presented here (Table 3), up until the end of 2017. The three more recent novae with LAT detections are V357 Mus (also known as Nova Mus 2018 or PNV J11261220-6531086; Li et al., 2018a), V392 Per (Nova Per 2018; Li et al., 2018b) and V906 Car (also known as ASASSN-18fv or Nova Car 2018; Jean et al., 2018) –
which was also detected by AGILE (Piano et al., 2018). In addition, the earlier nova V1324 Sco (Nova Sco 2012) was also seen in the γ-rays by the LAT (Ackermann et al., 2014), but was never detected in the X-ray band by Swift (Page et al., 2012c; Page & Osborne, 2013); V5856 Sgr (ASASSN-16ma; Nova Sgr 2016 No. 4) had a LAT detection (Li et al., 2016a,b, 2017), but was only weakly seen in hard X-rays (no SSS emission) by Swift (two observations were taken, 14.9 and 149.0 days after the nova discovery), so not included in this paper. Franckowiak et al. (2018) also lists V1535 Sco (included in this Swift sample) and V679 Car (Nova Car 2008; undetected by Swift) as γ-ray emitting candidates, with significances of around 2σ. Of this sample of LAT novae, V745 Sco and V1534 Sco (and V1535 Sco with the tentative detection) are symbiotic (also recurrent, in the case of V745 Sco) novae, while the others are ‘standard’ classical novae. Note that Fermi was launched on 2008 June 11, meaning that the earliest 11 novae in this Swift sample (Table 1) were not observed by LAT around outburst.

As more novae are detected at GeV energies, it appears possible that all novae are potential γ-ray sources. Given the relatively few GeV photons detected for any given nova, it is however likely that only nearby explosions would be detected, as discussed by Morris et al. (2017). Martin & Dubus (2013) consider the LAT detection of V407 Cyg, presenting a model where the γ-rays are caused by shock-accelerated electrons, while Shore et al. (2013) also conclude that internal shocks within the ejecta lead to the GeV emission in V959 Mon. The presence of shocks in nova systems is also revealed through radio data (e.g., Chomiuk et al., 2014b; Weston et al., 2016a); Metzger et al. (2014, 2015) propose that the reprocessing of early X-ray shocks by a dense, external shell may contribute significantly towards the optical/UV emission of novae. Early observations by Swift and NuSTAR (Nuclear Spectroscopic Telescope Array; Harrison et al., 2018) around the optical peak could provide additional information about this parameter space.

- Models of nova outbursts predict that there will be a short (0.5+ day) X-ray flash just after hydrogen ignition, but before the optical outburst. The duration of such a flash would be an indicator of the WD mass and accretion rate. However, catching a short flare in X-rays before the nova becomes optically bright requires either advance warning of an outburst (e.g., a recurrent nova with a well-known recurrence period), or all-sky
Table 3: Novae discussed in this paper which have a Fermi-LAT detection.

| Nova     | LAT detection reference                           |
|----------|--------------------------------------------------|
| V407 Cyg| Abdo et al. (2010)                               |
| V959 Mon| Cheung et al. (2012)                             |
| V339 Del| Hays et al. (2013)                               |
| V1369 Cen| Cheung et al. (2013a)                            |
| V745 Sco| Cheung et al. (2014)                             |
| V5668 Sgr| Cheung et al. (2015, 2016a)                      |
| V407 Lup| Cheung et al. (2016b)                             |
| V5855 Sgr| Li & Chomiuk (2016)                              |
| V549 Vel| Li & Strader (2017)                              |

X-ray surveys. Morii et al. (2016) placed limits on X-ray flashes for 40 novae using the Monitor of All-sky X-ray Image (MAXI; Matsuoka et al., 2009); however, the energy band of the Gas Slit Camera at 2–4 keV is likely too high to detect the expected SSS emission. The most rapidly recurrent nova known to date, M31N 2008-12a (Henze et al., 2018, and references therein), has a recurrence timescale of close to 1 yr, making it a suitable candidate for monitoring for precursive flashes. A high cadence (approximately every 6 hr) monitoring campaign was carried out by Swift during the 8-day run-up to the eventual 2015 outburst (Kato et al., 2016). No X-ray emission was detected in this interval, with the conclusion by Kato et al. (2016) being that the expected flash probably occurred ∼ 15.5 day pre-outburst, due to rapidly recurrent novae having lower maximum nuclear burning luminosities (despite their expected high WD masses). Future wide-field missions, such as Einstein Probe (Yuan et al., 2018), will hopefully detect these expected X-ray flashes, which can then be followed up with Swift.

5. Summary

Since its launch in 2004, Swift has observed in detail a large number of novae, leading to some interesting and unexpected results as highlighted here. This paper presents novae from 2006–2017, bringing together the Swift X-ray and UV light-curves of the well-monitored objects, almost all of which
had detected supersoft emission. This dataset would lend itself to future statistical studies, where the X-ray properties could be compared between the different speed-classes of the novae, for example.

*Swift* data are immediately public, and can be accessed online, at http://www.swift.ac.uk/archive/ql.php, within a few hours of the observation taking place; the data are then moved to the archive at http://www.swift.ac.uk/swift_live/ around a week later. An online XRT product generator is provided by the UK Swift Science Data Centre (UKSSDC) at http://www.swift.ac.uk/user_objects/ which can be used to generate spectra, light-curves and images (Evans et al., 2007, 2009).

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