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On a century of extragalactic novae and the rise of the rapid recurrent novae

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Abstract

Novae are the observable outcome of a transient thermonuclear runaway on the surface of an accreting white dwarf in a close binary system. Their high peak luminosity renders them visible in galaxies out beyond the distance of the Virgo Cluster. Over the past century, surveys of extragalactic novae, particularly within the nearby Andromeda Galaxy, have yielded substantial insights regarding the properties of their populations and sub-populations. The recent decade has seen the first detailed panchromatic studies of individual extragalactic novae and the discovery of two probably related sub-groups: the 'faint–fast' and the 'rapid recurrent' novae. In this review we summarise the past 100 years of extragalactic efforts, introduce the rapid recurrent sub-group, and look in detail at the remarkable faint–fast, and rapid recurrent, nova M31N 2008-12a. We end with a brief look forward, not to the next 100 years, but the next few decades, and the study of novae in the upcoming era of wide-field and multi-messenger time-domain surveys.

Keywords: novae, cataclysmic variables — X-rays: binaries — stars: individual (M31N 2008-12a)

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1. Introduction

A long time ago in a galaxy far, far away.... (Kurtz & Lucas, 1977): in 1909 a pair of nova eruptions in the 2.5 Mly distant Andromeda Galaxy (M 31) were discovered and followed photographically by George Ritchey (1917).

Fast forward a hundred years to the present day and we have discovered over 1,100 nova eruptions in M 31, have studied novae in almost two dozen galaxies, and have gained tremendous insights into nova physics and evolution from dedicated multi-wavelength surveys of extragalactic nova populations. At the threshold of a new golden age of multi-messenger time-domain surveys, we present a detailed review of many of the lessons learnt on the road so far.

The last extensive review of extragalactic nova populations was presented by Shafter et al. (2014), but this predated major multi-wavelength surveys, the rise of amateur observers, and the discovery of the 'rapid recurrent novae' (RRNe). Darnley (2017) presented a brief review of the prototype RRN M31N 2008-12a, but much has been discovered since then. In this review we will summarise the last century of extragalactic nova work, focussing in more detail on the last decade. We will introduce the rapidly expanding field of extragalactic novae, particular the newly discovered RRN subgroup with recurrence periods $P_{\rm rec} \leq 10$ yrs, along with the annually erupting M31N 2008-12a. We will end with a look forward to the next few decades.

2. Prerequisites

Here we briefly summarise those aspects of nova astrophysics that will not be covered in detail in this review, yet are a necessary foundation and context for understanding the following sections.

2.1. Nova physics: interacting binaries

A classical nova (CN) eruption is the result of a thermonuclear runaway (TNR) on the surface of an accreting white dwarf (WD; see Schatzman, 1949, 1951; Gurevitch & Lebedinsky, 1957; Cameron, 1959; Starrfield et al., 1972, 1976, 2008, 2016; Prialnik et al., 1978; José, 2016, for the early history and recent reviews). The TNR occurs following the accumulation of hydrogen-rich material from a donor star onto the WD within a close binary system.

Novae are a class of cataclysmic variable (CV; see Sanford, 1949; Joy, 1954; Kraft, 1964; Warner, 1995), where the donor is typically a late-type main sequence star and mass transfer usually proceeds through an accretion disk surrounding the WD. There are (observationally) small subclasses where magnetic accretion or accretion columns play a role, and systems with further evolved donors; sub-giants or red giants (Darnley et al., 2012).

2.2. Multi-wavelength emission

The TNR drives the ejection of material from the WD's surface at relatively high velocities. The expanding pseudophotosphere (PP) of the initially optically-thick ejecta results in a rapid increase in luminosity (see Bode & Evans,

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2008; Woudt & Ribeiro, 2014, for anthologies of recent reviews). What one observes depends upon the structure and geometry of those ejecta, and the emission and absorption processes within. In general, the observed radio, infrared (IR), optical, and ultraviolet (UV) emissions reflect the characteristics of the ejected shell.

Following the TNR, nuclear burning continues on the WD surface in quasi-hydrostatic equilibrium, until the accreted fuel source is exhausted (Prialnik et al., 1978). As the ejecta become optically thin, the PP recedes back to the WD, with peak emission migrating to shorter wavelengths. If the ejecta become fully transparent before the nuclear burning ceases, the underlying 'super-soft X-ray source' (SSS) may be revealed (see, for e.g., Hachisu et al., 2006; Krautter, 2008; Osborne, 2015). Importantly, the visibility windows for the SSS emission are typically much longer (years to decades) than for the optical light (weeks to months; see, for e.g., Henze et al., 2014b).

2.3. Nova evolution and the supernova connection

It is widely accepted that all novae inherently recur. Following each eruption the WD and donor remain (relatively) unscathed and accretion may soon reestablish – allowing the cycle to begin anew. An observationally small sub-set, dubbed the recurrent novae (RNe), have been observed to undergo multiple eruptions. Observed values of P_{rec} range from 1 yr (Darnley et al., 2014b) up to 98 yrs (Pagnotta et al., 2009). It seems most likely that both ends of this scale are simply due to current observational limits.

Novae have long been heralded as one of the possible single-degenerate pathways toward type Ia supernovae (SNe Ia; see, for e.g., Whelan & Iben, 1973; Hachisu et al., 1999a,b; Hillebrandt & Niemeyer, 2000), as, to be absolutely fair, have almost all scenarios that allow a WD to increase in mass. But a number of questions regarding the viability of the nova pathway have been posed:

Do the WDs in novae increase in mass? This is particularly important as only CO WDs grow to produce SNe Ia; their ONe cousins result in an accretion-induced collapse to a neutron star (Gutierrez et al., 1996), once the Chandrasekhar (1931) mass is surpassed. Pioneering multi-cycle nova eruption models have now shown that the WDs do indeed increase in mass, with little or no tuning of the initial parameters (Hillman et al., 2014, 2015, 2016). A number of other authors have arrived at similar results (see, for e.g., Hernanz & José, 2008; Starrfield et al., 2012, 2019; Starrfield, 2014; Kato et al., 2017).

Are the WDs in the RN systems – those already close to the Chandrasekhar mass – CO or ONe? To date, there remains no published evidence for super-Solar abundances of Ne in the ejecta of RNe (see, e.g., Mason, 2013).

Finally, are there simply enough novae, accreting at a high enough rate, to impart a measurable impact as a SN Ia pathway? We don't know (see Section 5). But, if novae do provide a significant channel then they hold an advantage over other progenitors, they are by far the most luminous, allowing their populations to be studied out to ~ 20 Mpc (see, for e.g., Curtin et al., 2015), and beyond.

2.4. The advantages and drawbacks of Galactic novae

Novae in the Galaxy, and even in the Magellanic Clouds, have been studied individually in increasingly exquisite detail across the electromagnetic spectrum (see, for e.g., Hounsell et al., 2010, 2016; Bode et al., 2016; Aydi et al., 2018b). Even early-eruption γ-ray emission is now routinely observed from Galactic novae (see, for e.g., Abdo et al., 2010; Ackermann et al., 2014), although the underlying mechanism is yet to be fully understood (see Chomiuk et al., 2014). With current capabilities, any γ-rays can only be detected from nearby Galactic novae and hard X-ray detections from the eruptions (not to mention during quiescence) are almost exclusively restricted to Milky Way systems (there is some evidence for early post-eruption hard X-ray emission from the 2016 eruption of the RN LMC 1968; Darnley et al., 2016b; Kuin et al., 2019).

Our *privileged* location within the spiral structure of the Milky Way (and the irregular nature of the LMC and SMC) severely limits the ability to undertake unbiased studies of the population(s) of Galactic or similarly nearby novae. While the second data release (DR2) from the *Gaia* mission (Gaia Collaboration et al., 2016, 2018) may have removed some ambiguity from Galactic distance estimates (see the discussions in Schaefer 2018 and Selvelli & Gilmozzi 2019), we must wait for at least the fourth release (DR4) until the potential systematics (in part due to the orbital motion of the unresolved nova binaries; see, for e.g., Lindegren et al., 2018) can be investigated.

There remain uncertainties on the gas and dust columns toward each Galactic nova that severely impact their (individual and) population studies, with potentially only a small fraction of Galactic novae observable (and even less observed; Schaefer, 2014; Shafter, 2017). The trials and tribulations of inferring the Galactic rate from a small spatially constrained sample has led to estimates that range from 11 yr^{-1} (Ciardullo et al., 1990b) to 260 yr^{-1} (Sharov, 1972). The most plausible estimate of the Galactic nova rate is perhaps the most recent (but relatively unconstrained) of $50^{+31}_{-23}\,\mathrm{yr}^{-1}$ (Shafter, 2017).

3. Extragalactic novae

To minimise the effects of distance and extinction uncertainties, we turn to the study of extragalactic nova populations. And while still far from ideal, the close to edge-on M 31 (77° inclination; de Vaucouleurs, 1958) is the preferred laboratory for such studies. At a distance of 752 ± 17 kpc (Freedman et al., 2001) and experiencing a foreground reddening of $E\,(B-V) \approx 0.1$ (Stark et al., 1992), eruptions of the entire peak-luminosity range of M 31 novae are readily accessible to professional and amateur astronomers alike. Techniques, such as narrowband Hα imaging (Ciardullo et al., 1987), or difference image analysis (Kerins et al., 2010), allow the recovery of transients down to the central $\sim 10''$ (~ 40 pc) of the bright M 31 bulge.

3.1. A century of M31 novae: surveys and nova rates

As stated by Edwin Hubble (1929), "In 1885 interest in (M 31) was stimulated by the appearance of a nova very close to the nucleus". That 'nova', S Andromedae (Hartwig, 1885; Ward, 1885), turned out to be a SN explosion (SN 1885A; see discussion by de Vaucouleurs & Corwin, 1985). While a handful of M 31 nova candidates were retroactively found in 1909 data (Ritchey, 1917; Hubble, 1929), the first confirmed eruptions were a pair discovered (by Hubble) in 1932 and observed spectroscopically by Milton Humason (1932) from the Mount Wilson Observatory[1]. In the following century, the number of nova candidates in M 31 has grown beyond 1,100[2]. The number of spectroscopically confirmed M 31 novae now exceeds 200 (Shafter et al., 2011b; Ransome et al., 2019).

The most famous M 31 nova survey was the first, but not due to the novae. Along with the first extragalactic nova sample, Hubble (1929) published the first catalogue of Cepheid variables in M 31. The latter of course led directly to a distance determination toward M 31 (Hubble, 1929) and ultimately the understanding of the scale of the Universe and the essence of galaxies — settling the 'Great Debate' of 1920 between Harlow Shapley and Heber Curtis (see Shapley & Curtis, 1921, for a transcript of that debate). From the 85 nova candidates included in his catalogue, Hubble estimated a global M 31 rate of $\sim 30\,\mathrm{yr}^{-1}$.

Subsequent surveys of novae in M 31 are summarised in Table 1 together with the evolution of estimates of the galaxy-wide eruption rate. Around half the M 31 nova candidates have been discovered by these surveys; the remainder by all-sky (particularly SN) surveys or by individuals. Special mention must be made of the exceptional efforts of Kamil Hornoch, and the amateur astronomer team of Koichi Nishiyama and Fujio Kabashima, who between them have discovered in excess of 200 M 31 novae.

Table 1: A summary of the principal M 31 nova surveys.

Survey	Novae	Rate [yr^{-1}]
Hubble (1929)	85	~ 30
Arp (1956)	30	24 ± 4
Capaccioli et al. (1989)†	142	29 ± 4
Ciardullo et al. (1987, 1990a)	40	...
Sharov & Alksnis (1991, 1992)	33	...
Tomaney & Shafter (1992)	9	...
Rector et al. (1999)	44	...
Shafter & Irby (2001)	72	37^{+12}_{-8}
Darnley et al. (2004, 2006)‡	20	65^{+16}_{-15}
Feeney et al. (2005)‡	19	...
Shafter et al. (2011b)	44	...
Kasliwal et al. (2011)	6	...
Cao et al. (2012)	29	...
Lee et al. (2012)	91	...
Ransome et al. (2019)	180	...

†Capaccioli et al. (1989) presents a combined analysis of the three Asiago surveys (Rosino, 1964, 1973; Rosino et al., 1989).
‡Darnley et al. (2004, 2006) and Feeney et al. (2005) reported independent analyses of the the POINT-AGAPE microlensing survey data (see Aurière et al., 2001).

The most recent observational determination of the M 31 nova rate was produced by Darnley et al. (2004, 2006), who used a high-cadence, multi-colour survey to estimate a rate of $65^{+16}_{-15}\,\mathrm{yr}^{-1}$ — almost twice that of previous studies. Being the first to implement an 'automated' nova survey, that exclusively used algorithms to detect and classify novae, Darnley et al. found that the M 31 nova distribution closely followed a combination of the bulge and disk light of the host. They also reported that while the novae were therefore clustered around the central bulge, the disk contribution to the overall population was also significant: with rates of 38^{+15}_{-12} (bulge)[3] and 27^{+19}_{-15} (disk), see Section 3.4 for further discussion.

This high global rate is consistent with the large numbers of novae now routinely discovered each year in M 31, particularly as larger area detectors and all-sky surveys have improved spatial and temporal coverage of the galaxy.

There are a number of reasons why the earlier surveys resulted in relatively low determined rates. Arp (1956) and Rosino (1964, 1973) both reported a substantial decrease in the nova population toward the centre of the bulge – however, this was a selection effect due to surface brightness limitations at the time. Using narrowband Hα observations, which are not as affected by the central surface brightness, Ciardullo et al. (1987) was the first to propose that the nova distribution followed the M 31 galactic light all the way into the centre. Many of the earlier surveys concentrated on the bulge (and therefore simply missed the disk novae) or may have over estimated completeness (see Darnley et al., 2006, for a relevant discussion). To address this, Shafter & Irby (2001) extended their survey to cover the M 31 disk, but reported that the nova distribution is (still) consistent with an association to the bulge.

3.2. Selection effects and corrections

Despite its advances, when we look in more detail at the Darnley et al. (2004, 2006) work, we note that their survey did not detect any novae with speed classes (the time

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[1] From the description given in Humason (1932), it is possible that M31N 1925-09a may have been spectroscopically confirmed via a slit-less spectrum taken by that author.

[2] According to the on-line extragalactic nova database of Pietsch (2010): `http://www.mpe.mpg.de/~m31novae/index.php`

[3] Note that the reported bulge rate is similar to the M 31-wide 'bulge dominated' rate of Shafter & Irby (2001).

taken for a nova to decay by two magnitudes from peak brightness; Payne-Gaposchkin, 1964) $t_2 \lesssim 10$ days, nor any with $t_2 \gtrsim 215$ days[4]. The subsequent completeness analysis did not include any novae with speed classes beyond the observed range. The computed rates are therefore only applicable to the quoted t_2 range and as such *are lower limits when considering the entire eruptive population.*

With that limitation in mind, Soraisam et al. (2016) utilised the Arp (1956, which contains numerous fast, $t_2 \leq 20$ d, novae) catalogue with the Darnley et al. catalogue to attempt to correct for the latter's completeness bias. Soraisam et al. assume that the M 31 novae follow the galactic light and found that $\sim 30\%$ of M 31 novae must be fast ($t_2 < 10$ days), yielding a corrected rate $\approx 106\,\mathrm{yr}^{-1}$. Chen et al. (2016) coupled a population synthesis approach with the nova eruption model from Darnley et al. (2006, also see Section 3.4) to derive an M 31 rate of $97\,\mathrm{yr}^{-1}$, again indicating a 'missing' population of the fastest novae. To date a large population of very fast M 31 novae has not been uncovered (also see Section 4), but we do note that there has not been a dedicated campaign to detect such eruptions.

3.3. Studies of individual extragalactic novae

The last decade has seen a rapid development in the scope of observations toward individual extragalactic novae. Historically, observations of M 31 novae typically consisted of sparsely populated light curves and the occasional spectrum. Now, Local Group novae are routinely spectroscopically confirmed, often have detailed multi-colour optical light curves, plus the inclusion of UV and X-ray observations, even late-time infrared observations have been attempted utilising *Spitzer* (Shafter et al., 2011a).

This era of extensive panchromatic studies of extragalactic novae began in earnest in 2007 when four separate eruptions were examined in detail. M31N 2007-11a was one of the first M 31 novae to be studied extensively in the optical and X-ray (the latter via *Chandra* and *XMM-Newton*; Henze et al., 2009b). The slowly rising yet luminous M31N 2007-11d was among the first to be studied in detail optically and with multiple epochs of spectroscopy (Shafter et al., 2009). A study of the RN *candidate* M31N 2007-12b quickly followed (Bode et al., 2009), which combined photometric and spectroscopic evolution with a Neil Gehrels *Swift* Observatory detection of the SSS, and the first recovery of a nova progenitor system (which contains a red giant donor) beyond the Milky Way. Further analysis of 2007-12b by Pietsch et al. (2011) reported additional SSS observations, likely measured the WD rotation period (and potentially the orbital period), and proposed that the system may be an intermediate polar (see Krzeminski 1977 and Warner 1983). Finally, M31N 2007-06b became the first CN in an M 31 Globular Cluster (GC) discovered optically (Shafter & Quimby, 2007) and subsequently detected in X-rays (Henze et al., 2009a).

But it is M31N 2008-12a, first discovered optically the following year, that has become by far the best studied extragalactic nova to date — we devote Section 6 entirely to that remarkable system.

3.4. Multiple populations within a single host

The proposal that multiple nova populations may coexist in the same galaxy was initially postulated by Duerbeck (1990) and was expanded by Della Valle et al. (1992). A two-population model was formulated due to evidence for bright–fast novae showing association with the Milky Way 'thin disk', whereas the faint–slow novae arose from a more spatially extended 'thick disk' or bulge population. Della Valle & Livio (1998) further proposed that the bright–fast novae all belonged to the He/N taxonomic spectral class (see Williams, 1992, 2012) and were all located at scale heights within 100 pc of the Galactic plane, contained high mass WDs (M_{WD}) and were related to Population I (relatively young). In contrast, the faint–slow novae were typically Fe II novae that extended up to ~ 1 kpc beyond the plane, contain low M_{WD} and are Population II (relatively old). This result has been questioned by Özdönmez et al. (2018) who did not find evidence for slow or fast, or Fe II or He/N, novae having different Galactic scale height distributions, but instead found that all novae are largely concentrated within the Galactic disk – a result that they predominantly put down to advances in catalogue completeness, particularly spectroscopically. The spatial distribution of Galactic novae has, however, yet to be studied in a post-Gaia era, so the apparent contradiction between these two studies may soon be understood.

In M 31, the work by Ciardullo et al. (1987), Capaccioli et al. (1989), and Shafter & Irby (2001) reported a strong association between the bulge light and the nova distribution – with little evidence for a *substantial* disk contribution[5]. Of course, selection effects may have played some part. If faster novae do tend to reside in the disk (as proposed by Della Valle et al., 1992), then survey cadence could impact the ability to detect disk novae.

Ciardullo et al. (1987), Shafter & Irby (2001), and Darnley et al. (2006) each presented a single parameter model for the nova distribution within M 31:

$$\Psi_i = \frac{\theta \mathscr{L}_i^d + \mathscr{L}_i^b}{\theta \sum_i \mathscr{L}_i^d + \sum_i \mathscr{L}_i^b}, \tag{1}$$

where Ψ_i is the probability of a nova erupting at a given location, i, that has a contribution $\mathscr{L}_i^d + \mathscr{L}_i^b$ from the disk and bulge light, respectively. The wavelength dependant parameter θ is the ratio of the disk and bulge eruption rates per unit light. This approach allows exploration of

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[4] This was, in part, due to the choices made when designing the detection algorithms, as An et al. (2004) and Feeney et al. (2005), who both also used the POINT-AGAPE data set, discovered a handful of faster novae that were not in the Darnley et al. catalogue.

[5] The disk contribution required to match observations has evolved upward with time.

the population distribution(s) without explicitly assigning a 'bulge' or 'disk' origin to individual novae. Due to a limited number of novae and a bulge dominated survey, Ciardullo et al. were restricted to placing an upper limit of $\theta < 0.1$ — i.e. a bulge dominated population ($\theta = 0$ represents a bulge *only* population). Shafter & Irby derived $\theta = 0.41^{+0.40}_{-0.25}$ by considering the B-band galactic light.

The Darnley et al. (2006) analysis led to a determination of $\theta = 0.18^{+0.24}_{-0.10}$ (when considering the r'-band M 31 light[6]), i.e. the bulge nova rate per unit light is ~ 5 times that of the disk, and ruled out that the novae follow the r'-band light (i.e. $\theta = 1$) of M 31 at beyond the 95% level — thereby lending strong support to separate 'bulge' and 'disk' populations.

Shafter et al. (2011b) presented a spectroscopic and photometric catalogue of 46 M 31 novae, bringing (at the time) the number of spectroscopically confirmed systems up to 91. This work confirmed that the M 31 proportion of Fe II (82%) and He/N (18%) novae was consistent with that measured in the Milky Way (Della Valle & Livio, 1998; Shafter, 2007). By combining their data set with that of Capaccioli et al. (1989), Shafter et al. demonstrated that the M 31 'fast novae' ($t_2 \leq 25\,\mathrm{d}$) were more spatially extended than their slower counterparts ($t_2 > 25\,\mathrm{d}$), as might be expected if a younger disk population contained novae with on average higher M_{WD} (as proposed by Della Valle et al., 1992, for the Milky Way). However, Shafter et al. were unable to find compelling evidence for a difference in the spatial distribution of the M 31 Fe II and He/N novae.

Combining the nova catalogue of Shafter et al. (2011b) and multi-waveband *Hubble Space Telescope (HST)* imaging of the north-eastern half of M 31 (the PHAT survey; Dalcanton et al., 2012), Williams et al. (2014b) undertook the first extragalactic survey for nova progenitor systems. From an input catalogue of 38 novae, Williams et al. recovered the progenitors of 11 systems – those harbouring giant donors and/or bright accretion disks (both potential indicators of a high mass accretion rate, $\dot{M}$). The subsequent statistical analysis found the proportion of M 31 novae with luminous progenitors is $30^{+13}_{-10}\%$ ($> 10\%$ at the 99% confidence level; Williams et al., 2016). This analysis also indicated that these luminous progenitors were more likely to be associated with the disk population, and the authors could not formally exclude the possibility that all of these systems were disk novae (Williams et al., 2016).

3.5. The X-ray properties of Andromeda Galaxy novae

A new and crucial angle was added to the nova population research when Pietsch et al. (2005) used their existing large *XMM-Newton* surveys of M 31 and M 33 to specifically identify nova X-ray counterparts — increasing the M 31 sample size by more than a factor of four[7]. While the nova rate in M 33 is too low to allow a population approach, the M 31 numbers were significant. Pietsch et al. (2005) concluded that nova eruptions are the main source of transient SSSs in M 31. In a follow-up study, Pietsch et al. (2007) analysed more recent archival *Chandra* and *XMM-Newton* data to find additional novae — among them objects with unexpectedly short SSS states of only a few months alongside novae that remained X-ray bright almost a decade post-eruption. The superior performance of this new generation of large X-ray telescopes, *XMM-Newton* and *Chandra*, was promising strong synergies with the high nova rate of M 31.

Building upon those pioneering surveys, Henze et al. (2010, 2011, 2014b) undertook a series of X-ray surveys between 2006 and 2012. These surveys were designed specifically for nova discovery: they used cadences of 10 days to study short SSS phases, focussed only on the bulge of M 31 where most novae are found, and used a coordinated observing strategy of *XMM-Newton* and *Chandra* pointings to cover the galaxy during a continuous 3-4 months[8]. The unparalleled spatial resolution of *Chandra* allowed the first X-ray detections of novae close to the M 31 core. The superior effective area of *XMM-Newton* provided the depth to detect faint sources and perform low-resolution spectroscopy for the brighter ones.

By the final paper of the series, Henze et al. (2014b) had increased the sample size of M 31 novae with X-ray detections to 79 and derived a large set of SSS parameters alongside optical properties from support or community observations. *For the first time, it was possible to study the X-ray vs optical parameters of novae using population statistics.* Henze et al. (2010) had found a correlation between the optical decline time and the duration of the SSS phase, confirming a similar result found for Galactic novae (Schwarz et al., 2011). Henze et al. (2010) also reported tentative evidence for differing X-ray properties between M 31 bulge and disk novae.

Using the complete sample, Henze et al. (2014b) discovered strong correlations between five fundamental observable nova parameters: the 'turn-on' (t_{on}) and 'turn-off' (t_{off}) times of the SSS, the SSS black-body (BB) effective temperature[9] ($k_{\mathrm{B}}T$), the optical decline time (t_2), and the ejecta expansion velocity (v_{exp}) as derived from optical spectra. Many of these relations are now routinely used in the planning of extragalactic X-ray observations of novae. In essence: *novae that decline fast in the optical have short and high-temperature SSS states.* In Figure 1 we show correlations based on Henze et al. (2014b) and here we reproduce the corresponding best fits:

$$t_{\mathrm{on}} = 10^{(0.8\pm0.1)} \cdot t_{2,R}^{(0.9\pm0.1)}\ [\mathrm{days}]\,, \tag{2}$$

$$t_{\mathrm{on}} = 10^{(5.6\pm0.5)} \cdot v_{\mathrm{exp}}^{(-1.2\pm0.1)}\ [\mathrm{days}]\,, \tag{3}$$

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[6] 1σ confidence limits, the distribution is non-Gaussian.

[7] They also utilised archival M 31 data from *ROSAT* (see surveys by Greiner et al., 1996, 2004) and *Chandra*.

[8] The small Sun angle of M 31 during part of the year strongly affects visibility especially for *XMM-Newton*.

[9] SSS spectra are not BBs (see, for e.g., Ness et al., 2013, among many others), yet BB fits can serve as a consistent parametrisation.

$$t_{\rm off} = 10^{(0.9\pm0.1)} \cdot t_{\rm on}^{(0.8\pm0.1)}\ [\text{days}]\,, \tag{4}$$

$$t_{\rm off} = 10^{(6.3\pm0.5)} \cdot (k_{\rm B}T)^{(-2.3\pm0.3)}\ [\text{days}]\,, \tag{5}$$

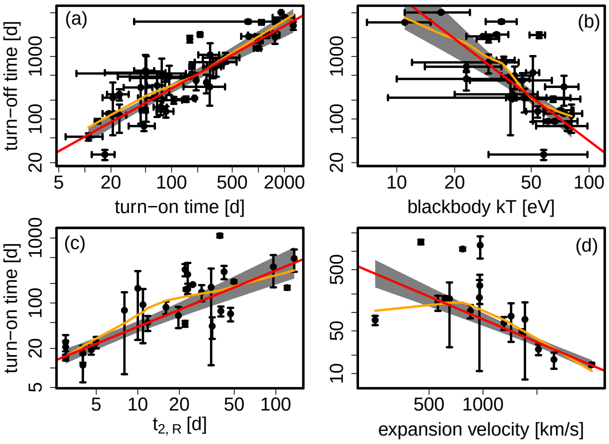

Figure 1: M 31 nova X-ray vs optical correlations based on Henze et al. (2014b). Black: data; orange: smooth fit for visualisation; red: robust power-law fit with corresponding 95% confidence regions.

Beyond being a powerful tool for understanding nova population physics, X-ray observations are crucial for discovering a rare subset of novae: those found in GCs. While the intrinsic brightness of (extragalactic) GCs renders optical nova detections difficult, there are no bright SSSs in GCs other than novae (but many harder X-ray sources). With two confirmed plus one likely GC novae (Henze et al., 2013), M 31 hosts three of the six known GC novae.

The first M 31 GC nova, M31N 2007-06b, was discovered in the optical by Shafter & Quimby (2007) and soon after in X-ray observations by Henze et al. (2009a, during their large nova survey). In the same survey season these authors discovered another GC SSS. Note that SSSs in GCs are also a very rare occurrence but that no optical counterpart was found for this object (yet a nova could not be excluded). The latest M 31 GC nova, M31N 2010-10f, was first found in a serendipitous X-ray observation and later confirmed optically (Henze et al., 2013). It is noteworthy that all three of the M 31 GC novae (candidates) exhibited a short SSS phase. An exploration of this observational property with theoretical models was carried out by Kato et al. (2013).

3.6. Beyond Andromeda

Nova eruptions have been detected in many of the Local Group galaxies, with nova rates determined for the largest constituents (see Table 2 for a summary of the most recently published rates). However, the populations of M 31 and the Milky Way, which constitute the vast majority of the Local Group stellar mass and therefore the vast majority of the nova eruptions, are by far the best studied.

Table 2: Nova rates for Local Group galaxies.

Galaxy	Rate [yr^{-1}]	Reference
Milky Way	50^{+31}_{-23}	Shafter (2017)
LMC	2.4 ± 0.8	Mróz et al. (2016)
SMC	0.9 ± 0.4	Mróz et al. (2016)
M 31†	65^{+16}_{-15}	Darnley et al. (2006)
M 32‡	2^{+2}_{-1}	Neill & Shara (2005)
M 33	2.5 ± 1.0	Williams & Shafter (2004)
M 110‡	2^{+2}_{-1}	Neill & Shara (2005)
NGC 147‡	< 2	Neill & Shara (2005)
NGC 185‡	< 1.8	Neill & Shara (2005)

† See discussion about a possible elevated rate in Section 3.1.
‡ The Neill & Shara rates are estimates based upon a single nova in each of M 32 and M 110, and no detections in NGC 147 or NGC 185.

Shafter et al. (2012a) published the first photometric and spectroscopic analysis of the nova population of M 33. This catalogue contained 36 novae (the majority drawn from the literature) of which 8 yielded spectra (6 newly reported), and directly compared the M 33 population to that of M 31 (largely following Shafter et al., 2011b). Unlike M 31, Shafter et al. found that most M 33 novae (5/8) belonged to the He/N spectral class, and that only two novae were clearly Fe II (cf. 82% for M 31). Those authors concluded that the spectroscopic mix of M 33 novae differed from that of M 31 at the 99% confidence level.

In the LMC, Shafter (2013) again confirmed the connection between spectral type and decline time. As with M 33, only around half of the LMC novae were classified as Fe II, and the LMC nova population is more rapidly evolving than that of the Milky Way and M 31. Shafter proposed that the LMC nova population is younger than that of the M 31 bulge, and therefore contains *on average* higher mass WDs that evolve more rapidly. Shafter also comments on the large proportion of known RNe within the LMC population (∼ 10% of systems, or ∼ 16% of eruptions).

Recently, individual novae have been studied in detail in IC 1613 (Williams et al., 2017) and NGC 6822 (Healy et al., 2019), both hosts are dwarf irregular galaxies in the Local Group and, like the Magellanic Clouds, provide further examples of novae in low metallicity environments (see the discussion within Orio, 2013).

3.7. Beyond the Local Group and the 'LSNR'

The study of extragalactic novae is not constrained to the Local Group. In Table 3 we provide a summary of some of the more distant extragalactic nova work – out to, and including, the Virgo Cluster. A recent highlight within that realm is the results of a *HST* survey toward M 87 by Shara et al. (2016). In a similar vein to the POINT-AGAPE survey of M 31 (see Section 3.1), a micro-lensing survey was repurposed to study nova eruptions. In a result entirely independent of an earlier yet similar one presented in Shara & Zurek (2002), Shara et al. (2016) derived a nova rate for that giant elliptical galaxy of $\sim 400\,\text{yr}^{-1}$. As noted by Shafter et al. (2017b), that rate is over double

Table 3: Nova rates for galaxies beyond the Local Group.

Galaxy	Rate $[\mathrm{yr}^{-1}]$	Reference
M 49	189^{+26}_{-22}	Curtin et al. (2015)
M 51	18 ± 7	Shafter et al. (2000)
M 81	33^{+13}_{-8}	Neill & Shara (2004)
M 84	95^{+15}_{-14}	Curtin et al. (2015)
M 87	363^{+33}_{-45}	Shara et al. (2016)
M 94	$5.0^{+1.8}_{-1.4}$	Güth et al. (2010)
M 100	~ 25	Ferrarese et al. (1996)
M 101	$11.7^{+1.9}_{-1.5}$	Coelho et al. (2008)
NGC 1316	135 ± 45	Della Valle & Gilmozzi (2002)
NGC 2403	$2.0^{+0.5}_{-0.3}$	Franck et al. (2012)
NGC 5128	8.0 ± 2.8	Ciardullo et al. (1990b)

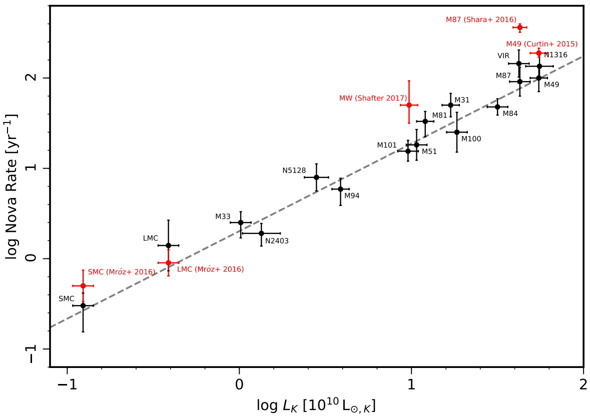

Figure 2: 'Luminosity Specific Nova Rate' (LSNR) based on the K-band luminosity of the host galaxy, using data from (Shafter et al., 2014, see their Figure 1).

those derived from ground-based observations (see Shafter et al., 2000; Curtin et al., 2015). Shafter et al. undertook an independent analysis of the *HST* data reporting that their results "are in general agreement" with Shara et al. (2016). But Shafter et al. urge caution, particularly when deriving nova rates using unconfirmed (spectroscopically) nova eruptions and especially when extrapolating a rate beyond the constraints of the survey data.

The 'Luminosity Specific Nova Rate' (LSNR) was first introduced by Ciardullo et al. (1990a,b) to compare the nova rates of the M 31 bulge and the elliptical component of NGC 5128. The LSNR employs a galaxy's integrated K-band luminosity as a proxy for the total stellar mass and permits direct comparison between the nova rates in different galaxies and between galaxies of differing morphological type. Shafter et al. (2014) presented a comprehensive review of the evolution and current status of the LSNR. In Figure 2 we reproduce the LSNR as computed by Shafter et al. who concluded that the nova rate is (simply) proportional to the K-band luminosity of the host (the grey dashed line). Those authors also found no evidence for the LSNR varying significantly with Hubble type.

Since 2014, new analyses of the Magellanic Clouds (Mróz et al., 2016), M 49 (Curtin et al., 2015), M 87 (Shara et al., 2016), and the Milky Way (Shafter, 2017, see Section 1) have been published. With the possible exception of the Clouds, each author has reported an elevated nova rate (see the red points in Figure 2). As summarised by Shafter (2017), there is now evidence for the LSNR being 3–4 times higher than the adopted value of ~ 2 novae per year per $10^{10}\,\mathrm{L}_{\odot,K}$ (as computed by Shafter et al., 2014). It is, perhaps, the limitations of previous surveys that led to underestimated nova rates. Transient surveys are particularly sensitive to the choice of cadence and the actual temporal sampling achieved, but the depth of extragalactic nova surveys may also be a limiting factor — one that is perhaps now been bridged by high spatial and temporal resolution *HST* surveys of M 87 (Shara et al., 2016), which can probe any populations of faint yet fast novae.

4. The 'MMRD' and the 'faint–fast' novae

No review of nova populations would be complete without a nod to the maximum magnitude—rate of decline relationship (MMRD). Hubble (1929) first noted that the brighter an M 31 nova appeared at peak the more rapidly it diminished. Mclaughlin (1945) confirmed Hubble's result Galactically and dubbed the correlation the "life—luminosity relation". Over time, the concept that the brightest novae fade the fastest was accepted, the MMRD was refined and, seemingly being invariant to the host population, enabled novae to be touted as primary distance indicators (see, for e.g., Arp, 1956; Schmidt, 1957; Pfau, 1976; de Vaucouleurs, 1978; Cohen, 1985; Della Valle & Livio, 1995; Downes & Duerbeck, 2000). Being brighter than Cepheids at maximum, extragalactic novae seemed like a promising rung on the cosmic distance ladder.

But the MMRD has always been fraught with problems. Despite the best attempts, a scatter of ~ 0.5 mag has persisted. This and the long-held knowledge that the MMRD does not work well for all novae, particularly the RNe (see Schaefer, 2010)[10], hamstrings the relationship for distance determinations to Galactic systems. Even at its best, the MMRD is a population relationship and should not be used to estimate the distance to individual novae, Galactic or otherwise. Thus, despite some advantages over Cepheid variables, in practice employing novae as (extragalactic) distance indicators had never been observationally efficient.

In the last decade, evidence has slowly started to mount questioning even the concept of an MMRD. The Fast Transients In Nearest Galaxies (P60-FasTING) survey (a forerunner to the Palomar Transient Factory; PTF) was undertaken by the Palomar 60-inch telescope (Kasliwal et al.,

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[10] Mclaughlin (1945) noted that the Galactic recurrent RS Ophiuchi "may not be typical" and excluded that system from his analysis.

2011). This deep and high-cadence survey targeted extragalactic novae, particularly in M 31. Kasliwal et al. reported the discovery of a 'new' population of "faint–fast" novae — novae that populated the lower left quadrant of the MMRD phase-space. As pointed out by Kasliwal et al., the M 31 faint–fast novae occupied a similar locus in MMRD-space as the Galactic RNe. We do note that the Kasliwal et al. sample were corrected for reddening internal to M 31 by use of the Balmer decrement. As shown specifically in Williams et al. (2017), this decrement should not be used to estimate reddening toward nova eruptions. But it seems unlikely that this should have severely affected the result.

It should be noted that now, almost a decade after the Kasliwal et al. study, a sizeable population of spectroscopically confirmed faint–fast novae has failed to materialise in M 31. This is despite an increased frequency and depth of coverage by professional and amateur observers alike. A compilation of previous surveys produced by Soraisam & Gilfanov (2015, see their Figure B.1) may also indicate a population of faint–fast novae, but also illustrates a very scattered distribution both above and below the traditional MMRD. Faint–fast novae are inherently challenging to discover, let alone observe spectroscopically, it is clear that more work is required locally to understand the true extent of the faint–fast population.

While the situation in M 31 remains puzzling, there is more serious trouble brewing for the MMRD in a galaxy further away: Shara et al. (2017) published an updated MMRD plot based on a daily-cadence *HST* M 87 survey (see Shara et al., 2016). The M 87 sample is much less likely (than M 31 novae) to be affected by reddening internal to M 87. Here Shara et al. propose (see their Figure 1) that the faint–fast population seen in *both* M 31 and M 87 severely undermines the validity of the MMRD relationship. To quote Shara et al. directly, "The fact that these (faint–fast) novae are both common and ubiquitous demonstrates that complete samples of extragalactic novae are not reliable standard candles, and that the MMRD should not be used in the era of precision cosmology either for cosmic distance determinations or the distances of Galactic novae."

With the availability of Gaia DR2 parallax distances, Schaefer (2018) was the first to re-assess the Galactic MMRD and came to similar conclusions. However, interestingly, Selvelli & Gilmozzi (2019) undertook a similar Gaia DR2 analysis using a different (but overlapping) sample to Schaefer, and concluded that Gaia *strengthened* the viability of the MMRD. Selvelli & Gilmozzi also demonstrated that the bolometric luminosity of novae correlates to the optical decline time (a 'maximum bolometric magnitude — rate of decline' relationship?), however, given that the same bolometric correction was used for each of their novae, this is perhaps not surprising — but we will return to this concept below. Selvelli & Gilmozzi went on to explore correlations between other nova system parameters, including $\dot{M}$, finding a correlation between $\dot{M}$ and decline time. The jury is still out on the Galactic MMRD; there is a clear need to understand the sample biases and extinction uncertainties. But the less-biased extragalactic samples indicate that the *original* MMRD concept – a monotonic relation between luminosity and decay rate – is flawed.

A number of authors have referred to the models of Prialnik & Kovetz (1995), which were later built on by Yaron et al. (2005), for theoretical grounding of the 'faint–fast' population. Those models indicate that the original MMRD novae, the "bright–fast" and "faint–slow" populations are powered by a combination of a high M_{WD} and low $\dot{M}$, or a low M_{WD} and high $\dot{M}$, respectively. The Yaron et al. models show that faint–fast novae may belong to a population of systems with high M_{WD} and high $\dot{M}$, the same fundamental system parameters as the RNe (as noted by Kasliwal et al., 2011). However, we note that Shara et al. (2017, see particularly their Figure 5) pointed out that the Yaron et al. grids could suggest that the total accreted envelope mass (rather than $\dot{M}$ explicitly) acts along with M_{WD} to explain the MMRD position of a given nova. When using grids of models we must consider the relative contribution to the observed population from a particular configuration, e.g. M_{WD} and $\dot{M}$. As shorter P_{rec} systems inherently produce more eruptions, we would expect faint–fast novae to always have a substantial contribution from RNe.

Yaron et al. also indicated that high M_{WD}—high $\dot{M}$ novae have low accreted envelope masses, therefore low mass ejecta. As we will see in Section 6, such a low ejected mass may lead to high velocity ejecta and a rapidly evolving eruption. But as shown by Darnley et al. (2016a), unlike CNe, the maximum PP radius for faint–fast novae corresponds to a much higher effective temperature (cf. ~ 8000 K for CNe; see Bode, 2010). Therefore, the peak energy output of the faint–fast novae occurs in the FUV or even EUV, compared to the optical for CNe.

Extending this argument, there is one quadrant of the MMRD that appears unpopulated, the upper right or "bright–slow" regime; where one might expect the eruptions of low M_{WD} with low $\dot{M}$ to reside. By comparison to faint–fast novae; bright–slow novae should have massive, slowly evolving, ejecta. As such, one might expect their peak to occur somewhere in the IR. But what exactly would such a slowly evolving IR-bright nova actually look like? Would we even identify it as a nova? Galactic examples of such novae *could* include systems like the epically-slow evolving V1280 Scorpii (see, e.g., Chesneau et al., 2012); or V723 Cassiopeiae, which exhibited a SSS so long it was considered a 'persistent SSS' (Ness et al., 2008; Schwarz et al., 2011) until it abruptly turned off in September 2015 (a SSS phase of almost 10 years; Ness et al., 2015). But more tantalising possibilities present themselves extragalactically. Kasliwal et al. (2017) published the initial results from 'SPIRITS', an extragalacitic IR transient survey undertaken with *Spitzer*. That paper presented 14 unusual transients those authors dubbed 'SPRITES' (eSPecially Red Intermediate-luminosity Transient Events). Kasliwal et al. noted that SPRITES sat in the IR luminosity gap between CNe and SNe, with some SPRITES exhibiting exceptionally slow evolution. With no discovered optical counterparts, perhaps some of the SPRITES fit the criteria of bright–slow novae from low $M_{\rm WD}$—low $\dot{M}$ systems? Shara et al. (2010) made similar claims regarding low $M_{\rm WD}$—low $\dot{M}$ novae and predicted that *some* (particularly 'M31-RV'; see Rich et al., 1989) of the 'luminous red novae' (LRNe; see, e.g., Munari et al., 2002; Williams et al., 2015) could be extremely slowly evolving CN eruptions[11].

Faint–fast novae evaded detection for years because faint–fast transients are just hard to find! But if they arise from high $M_{\rm WD}$—high $\dot{M}$ systems they are not inherently faint, they are just optically faint. Likewise, bright–slow novae may be IR bright but optically faint. As such, might there be hope for the MMRD concept yet? Perhaps some time should be taken to further explore the viability of the 'maximum *bolometric* magnitude—rate of decline' relationship, or the extension of the concept into a multi-parameter space spanned by the luminosity in different energy bands.

5. Recurring and rapidly recurring novae

A combination of a high $M_{\rm WD}$ and high $\dot{M}$ is required to drive a RN — by definition any nova that has been observed in eruption at least twice. The Galactic population of RNe has grown slowly and has remained at ten (see Schaefer, 2010, for a comprehensive review) since the addition of V2487 Ophiuchi a decade ago (Pagnotta et al., 2009). The small number is almost certainly a selection effect based mainly on increasing incompleteness as one looks back in time. It is probably not a coincidence that many of Galactic RNe have bright peak apparent magnitudes. The majority of the Galactic RNe are thought to contain a high $M_{\rm WD}$ and a high $\dot{M}$ maintained by an evolved donor; a sub-giant or red giant (Darnley et al., 2012, 2014a).

When LMCN 1968-12a erupted for a second time in 1990 it was widely claimed to be the first extragalactic RN (Shore et al., 1991). It was in fact only the first spectroscopically confirmed extragalactic RN. The honour of the first lies with M31N 1926-06a (the original eruption discovered by Hubble, 1929), whose recurrent nature was observed in 1962 independently by Rosino (1964) and Börngen (1968, see Henze et al. 2008). Since then, extragalactic RNe have only been discovered in the LMC and M 31, despite searches within the Local Group and beyond. In Table 4 we summarise the four currently known LMC RNe and the 18 within M 31.

The first catalogue of M 31 RN candidates was produced by Della Valle & Livio (1996, see their Table 3), who also assessed the RN populations of the LMC and Milky Way. Della Valle & Livio concluded that RNe could only contribute at the few percent level to the SN Ia rate in those hosts.

Table 4: RNe in the LMC (top) and M 31 (bottom).

Nova	Known eruptions	$P_{\rm rec}{}^{\dagger}$ $[{\rm yr}^{-1}]$	Refs
LMCN 1968-12a	4	6.7 ± 1.2	1
LMCN 1971-08a	2	~ 38	2
LMCN 1996	2	~ 22	3
YY Doradus	2	~ 67	4, 5
M31N 1919-09a	2	~ 79	6
M31N 1923-12c	2	~ 88	6
M31N 1926-06a	2	~ 37	6
M31N 1926-07c	3	~ 11	6
M31N 1945-09c	2	~ 27	6
M31N 1953-09b	2	~ 51	6
M31N 1960-12a	3	~ 6	6–8
M31N 1961-11a	2	~ 44	6
M31N 1963-09c	4	~ 5	6, 9
M31N 1966-09e	2	~ 41	6
M31N 1982-08b	2	~ 14	6
M31N 1984-07a	3	~ 8	6
M31N 1990-10a	3	~ 9	10
M31N 1997-11k	3	~ 4	6
M31N 2006-11c	2	~ 8	11
M31N 2007-10b	2	~ 10	12, 13
M31N 2007-11f	2	~ 9	14
M31N 2008-12a	14	0.99 ± 0.02	15, 16

For the equivalent Galactic table, see Schaefer (2010, their Table 21).
†To estimate $P_{\rm rec}$ we have (excluding LMCN 1968-12a and M31N 2008-12a) simply taken the shortest observed inter-eruption period.
References — (1) Kuin et al. (2019), (2) Bode et al. (2016), (3) Mróz & Udalski (2018), (4) Bond et al. (2004), (5) Mason et al. (2004), (6) Shafter et al. (2015), (7) Valcheva et al. (2019), (8) Soraisam et al. (2019), (9) Della Valle & Livio (1996), (10) Henze et al. (2016), (11) Hornoch & Shafter (2015), (12) Schmeer (2017), (13) Williams & Darnley (2017b), (14) Sin et al. (2017), (15) Darnley (2017), (16) this work.

The majority (all but three) of the most recent M 31 RN catalogue were identified by a monumental search of archival observations by Shafter et al. (2015). Those authors published a catalogue of 16 strong RN candidates, many of which were also spectroscopically confirmed, by virtue of astrometric arguments. Subsequently, three more M 31 RNe have been identified, M31N 2006-11c (Hornoch & Shafter, 2015), 2007-10b (Schmeer, 2017; Williams & Darnley, 2017b) and 2007-11f (Sin et al., 2017); 1990-10a has erupted again and halved its estimated $P_{\rm rec}$ (Henze et al., 2016), as has 1960-12a reducing its $P_{\rm rec}$ from ~ 53 to ~ 6 years (Valcheva et al., 2019; Soraisam et al., 2019), and 1966-08a has been confirmed to not be a RN.

M31N 1966-08a and its second eruption 1968-10c both hailed from the Rosino (1973) survey. Rosino noted "This star (1966-08a) coincides beyond any doubt with (1968-10c)", a fact on which Shafter et al. (2015) agrees. However, probably due to its (then) unprecedentedly short 'recurrence' period there were doubts. Sharov & Alksnis (1989) suggested that 1966-08a was more likely a foreground dwarf nova (DN) outburst. Both the 1966 and 1968 events were not observed spectroscopically, and nothing was seen from

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[11] We note that Tylenda et al. (2011) presented strong evidence for the LRN V1309 Scorpii being the merger of a compact binary.

this system for decades. Shafter et al. (2017a) recovered the progenitor system in archival Local Group Galaxies Survey (LGGS; Massey et al., 2006) and 2MASS (Skrutskie et al., 2006) data, which indicated a very low eruption amplitude for a nova (even given the potentially short P_{rec}). Follow-up spectroscopy, also reported by Shafter et al. indicated that the progenitor was a dwarf not a giant and was therefore incompatible with being in M 31. Shafter et al. proposed, based on the low amplitude and spectroscopy, that 1966-08a and its recurrence were the result of a Galactic flare star. Somewhat ironically, just days after that proposal by Shafter et al., another flare (the first in sixty years) from 1966-08a was discovered (Conseil, 2017a; Arce-Tord et al., 2017), followed soon after by another (Carey et al., 2019).

Long hailed as a RN, PT Andromedae (aka M31N 1957-10b) had been noted to recur five times (Alksnis & Zharova, 2000; Ruan & Gao, 2010; Zheng et al., 2010). Following spectroscopy of the 2010 event, Cao et al. (2012) suggested that PT And may be an M 31 RN. However, Shafter et al. (2015, and references therein) instead proposed a Galactic DN origin. Following another detection in 2017 (Conseil, 2017b), spectroscopy confirmed that PT And was not an M 31 nova but was consistent with a Galactic DN outburst (Williams & Darnley, 2017a,c).

Based on their statistical analysis of the M 31 RN and CN populations, Shafter et al. (2015) reported that $1/25^{\mathrm{th}}$ of detected M 31 eruptions arose from *known* RNe. Their completeness exercise indicated that as many as a third of M 31 eruptions could be from RNe ($P_{\mathrm{rec}} \leq 100$ yrs), broadly consistent with the independent findings of Pagnotta & Schaefer (2014) and Williams et al. (2016). Although relying upon a number of assumptions, Shafter et al. used their estimated M 31 RN population to compute the potential contribution to the SN Ia rate in that host, concluding it is unlikely that RNe provide a significant channel ($\sim 2\%$).

But if RNe play any important role in the production of SNe Ia, the key systems to find are those with WDs already close to the Chandrasekhar mass and accreting at a high rate. Those systems must be the ones with the shortest P_{rec} (Yaron et al., 2005; Kato et al., 2014; Hillman et al., 2016; Kato et al., 2017). Prior to 2013, the shortest confirmed P_{rec} belonged to the Galactic RN U Scorpii, which erupts every ~ 10 yrs (Schaefer, 2010). But, starting with the discovery of M31N 2008-12a (see Section 6), a population of 'rapid recurrent novae' (RRNe) has been uncovered.

We hereby, and admittedly arbitrarily, define a RRN as a system that has undergone eruptions less than a decade apart. Galactically, the only known example is U Sco, and in the LMC there is LMCN 1968-12a ($P_{\mathrm{rec}} = 6.7 \pm 1.2$; Kuin et al., 2019). But in M 31 there are eight (see Table 4) — *almost half of all known M 31 RNe.* Indeed, all new M 31 RNe since M31N 1984-07a are RRNe. In Figure 3 we illustrate the distribution of P_{rec} for the known RNe. These data indicate that the distribution of P_{rec} is relatively uniform across the three galaxies. We fervently note that these data likely suffer from multiple selection effects, there is no evidence to support that RRNe should only exist in M31, or that the 'peak' at $P_{\mathrm{rec}} \sim 10$ yr is real.

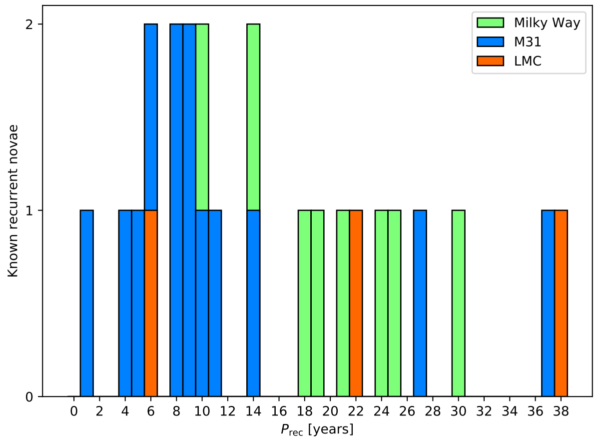

Figure 3: Distribution of recurrence periods of all known RNe ($P_{\mathrm{rec}} \leq 40$ yrs). RRNe are all those with $P_{\mathrm{rec}} \leq 10$ yrs and they largely exist within M 31. Data for Galactic RNe are from Schaefer (2010). The most rapidly recurring Galactic systems are the prototype sub-giant and red giant donor systems, U Sco and RS Oph, respectively.

This ten year threshold creates a phenomenological 'watch list' of RNe to study closely through multiple eruptions. Consistent analysis and comparison of multiple eruptions from individual systems will be a key future driver for extragalactic nova science. It would not be the last time that classification based on observed characteristics revealed physical insights.

So where are the Galactic RRNe? To date, the study of these systems has been largely confined to M 31 (but also see Kuin et al., 2019, for a detailed analysis of LMCN 1968-12a), which despite the advances in recent years severely limits observation opportunities to just optical to soft X-ray light curves and, in all but the most extreme case (see Section 6), optical spectroscopy. Given the high M_{WD}—high $\dot{M}$ requirements for a short P_{rec}, RRNe should be faint–fast novae. So it is not unlikely that the rapid-fire eruptions from Galactic RRNe might have been mistaken for other transients or even quasi-periodic variables, e.g., flare stars or DNe (the majority of which are not spectroscopically confirmed) — particularly before the discovery of the prototype system, M31N 2008-12a.

An open question – with direct connection to their ultimate fate – is just how many RRNe exist? Have we already uncovered the majority, or just scraped the surface? The rapidly approached era of all-sky, wide-field, (multi-messenger,) time-domain astronomy is key to addressing this question. Surveys such as the Zwicky Transient Facility (ZTF; Bellm et al., 2019) and the Large Synoptic Survey Telescope (LSST; Ivezić et al., 2019) are ideally placed to detect eruptions of RRNe Galactically, in the Local Group, and beyond. To classify and interrogate those eruptions, we are at the mercy of the availability of timely (and in this case, rapid) follow-up observations.

6. M31N 2008-12a — a remarkable recurrent nova

6.1. Innocuous beginnings

In-line with predictions (Darnley et al., 2006), there are now regularly over thirty novae discovered in M 31 each year[12]. So when a new eruption from a previously unknown system, M31N 2008-12a (hereafter '12a') was announced in 2008, there was nothing remarkable about this event except, perhaps, the date of the eruption, Christmas Day. The discovery note, written by Nishiyama & Kabashima (2008), simply contains a few sentences about the brightness of the eruption. No known follow-up observations were taken and the event was not spectroscopically confirmed.

In 2011, another eruption was detected by Korotkiy & Elenin (2011), while there were a handful of follow-up observations (Barsukova et al., 2011) there was no successful spectroscopy. In the available on-line material, a connection isn't made to the 2008 event, but the statement, "In SIMBAD object RX J0045.4+4154 located at a distance 3.79 asec" is made. RX J0045.4+4154 is, as we will see, intimately associated with 12a.

When the transient reappeared in 2012, again discovered by Nishiyama & Kabashima (2012), a single spectrum was obtained using the Hobby-Eberly Telescope (HET) by Shafter et al. (2012b). That spectrum (reproduced in Darnley et al., 2014b) confirmed that the 2012 event is clearly a nova eruption, within M 31, and revealed the characteristics of the He/N taxonomic class. In the reporting telegram, Shafter et al. make the link between the 2008, 2011, and 2012 events, and the first suggestion that the system may be a RN – despite the "unusually short interval between brightenings". Based on the RN hypothesis, an attempt was made to detect the SSS phase using *Swift*, but a series of four XRT (Burrows et al., 2005) observations beginning 20 days post-eruption failed to detect a source.

6.2. The realisation

The intermediate Palomar Transient Factory (iPTF; Law et al., 2009) reported the discovery of the 2013 event, which erupted on Nov 26 (Tang et al., 2013). Upon discovery, iPTF triggered follow-up spectroscopy, which again confirmed the eruptive nova nature (Tang et al., 2014). *Swift* observations began only six days post-eruption and found that the SSS was already visible (Henze et al., 2014a; Tang et al., 2014). At the time, this was the earliest on-set nova SSS to have been observed[13].

Darnley et al. (2014b) and Tang et al. (2014) compiled optical photometry of the 2013 eruption, which confirmed the 'under-luminous' nature of the eruptions (as reported in 2008, 2011, and 2012), and indicated an extremely rapid decline, i.e. faint–fast. Both Darnley et al. and Tang et al. utilised archival *HST* data to identify the likely progenitor system – a very blue system whose SED was consistent with a luminous accretion disk. In those initial analyses, no evidence for the mass donor was recovered.

Henze et al. (2014a) and Tang et al. (2014) both found three previous eruptions in the archives of *ROSAT* (1992 and 1993) and *Chandra* (2001), noting that the system was initially discovered as the "recurrent supersoft X-ray transient" RX J0045.4+4154 (White et al., 1995). Tang et al. also revealed that PTF detected an eruption in 2009.

Eruptions had been detected in 1992, 1993, 2001, 2008, 2009, 2011, 2012, and 2013. It seemed clear that the 2010 eruption had been missed, probably occurring during a gap in PTF coverage (Cao et al., 2012). The evidence presented by Darnley et al., Henze et al., and Tang et al. was strongly suggestive that 12a was a RN undergoing annual eruptions, and that it had been (at the time) doing so for at least twenty years. Therefore, it was concluded that 12a must contain a particularly massive WD and must be accreting an an elevated rate (Darnley et al., 2014b; Henze et al., 2014a; Tang et al., 2014), and all three publications ended with a prediction for the 2014 eruption.

6.3. 2010, 2014 and 2015, and a six month recurrence?

In light of predictions for a 2014 eruption, a programme was put together to monitor the 12a region of M 31. This was undertaken predominately by the Liverpool Telescope (LT; Steele et al., 2004), which detected the eruption on October 2. Upon detection, a pre-planned follow-up campaign was instigated that included multiple ground-based optical telescopes obtaining high-cadence photometry and a number of spectroscopic observations, and space-based UV and X-ray observations by *Swift*. Darnley et al. (2015, who addressed the optical and UV observations) reported that the 2014 eruption was similar to that of 2013 and that the nova evolved extremely rapidly ($t_2 = 1.8 \pm 0.1$ days) — faster than all known Galactic RNe. The first tentative evidence for a light-curve plateau, synonymous with the RN phenomenon (Hachisu et al., 2008; Schaefer, 2010; Strope et al., 2010; Pagnotta & Schaefer, 2014), the low peak optical luminosity was consistent with a low ejected mass, and the SEDs indicated a high photospheric temperature at maximum light. Darnley et al. also reported that seemingly low ejection velocity, obtained spectroscopically was consistent with models of a high $M_{\rm WD}$ and short cycle RNe (see, e.g., Yaron et al., 2005). The spectra also hinted at possible ejecta deceleration, similar to that seen in RS Oph (first noted after the 1958 eruption; Dufay et al., 1964) when the ejecta interact with pre-existing circumbinary material due to the red giant wind of that system's donor (Pottasch, 1967; Bode & Kahn, 1985; Bode et al., 2006). Henze et al. (2015b) reported on X-ray observations that showed a bright and rapidly evolving SSS with a fast turn-on ($t_{\rm on} = 5.9 \pm 0.5$ days) and short extent ($t_{\rm off} = 18.4 \pm 0.5$ d) — like the optical and UV, the 2014 X-ray evolution was very similar to that seen in 2013. Henze et al. revealed that a BB parameterisation of the X-ray spectrum indicated a very high effective temperature ($k_{\rm B}T = 120 \pm 5$ eV) and

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[12] `http://www.mpe.mpg.de/~m31novae/opt/m31/index.php`

[13] This was surpassed by the 2014 eruption of the RN V745 Scorpii, whose SSS turned-on 4 days post-discovery (Page et al., 2015).

that the X-ray light curve showed substantial variation over the first 10 days following the unveiling of the SSS. The derived X-ray parameters were also consistent with those predicted based on the M 31 population (Henze et al., 2010, 2011, 2014b, Section 3.5), and were consistent with a near-Chandrasekhar mass WD.

The most interesting finding reported by Darnley et al. (2015) was the discovery of extended nebulosity surrounding the system, which is discussed in more detail in Section 6.6. Darnley et al. and Henze et al. predicted that the 2015 eruption would occur between October and December.

The 2015 eruption represented a sea change. A concerted campaign was put together utilising facilities all around the globe including large numbers of observers from the American Association of Variable Star Observers (AAVSO[14]), the British Astronomical Association (BAA[15]), and the Variable Star Observers League in Japan (VSOLJ[16]) — a nova campaign not seen since the 2010 eruption of U Sco (see Schaefer et al., 2010). A space-based detection campaign was undertaken by *Swift* (Kato et al., 2016) in an attempt to capture the long-predicted nova precursor X-ray flash (XRF; Starrfield et al., 1990; Krautter, 2002; Kato et al., 2015; Hachisu et al., 2016). Early detection of the 2015 eruption was critical to the follow-up campaigns, which included rapid-response UV spectroscopy and photometry by *HST* and late-time ground-based spectroscopy from a number of 8m+ facilities[17].

The Las Cumbres Observatory network (LCO; Brown et al., 2013) made the discovery on August 28, however, *Swift* UVOT had detected the 2015 eruption marginally earlier[18]. The 2015 eruption occurred sooner than anticipated; the *Swift* XRF campaign had only just begun. Kato et al. (2016) reported a failed attempt to capture the XRF, citing the short lead-in time among the possible explanations. Another possibility presented is that although the XRF could 'escape' from the natal nova eruption it was largely absorbed by substantial circumbinary material. However, additional scenarios include insufficient *Swift* cadence or the XRF energy being incompatible with the *Swift* XRT (particularly given that instrument's low sensitivity to hard X-rays and the distance to M 31).

The follow-up campaign of the 2015 eruption obtained the most detailed optical (photometric and spectroscopic), UV, and X-ray datasets of any M 31 nova to date. Darnley et al. (2016a) presented and analysed a combined dataset from the 2013–2015 eruptions, which showed remarkable similarity at all energies, as suggested for RN eruptions by Schaefer (2010). Darnley et al. reported that the colour evolution was suggestive of a red giant donor, which was also supported by the strong evidence now seen for ejecta deceleration (see, e.g., Bode et al., 2006). Tentative evidence for high-excitation coronal lines was also presented, as might be expected in the presence of a shocked donor wind. Detailed SEDs provided no evidence for an optically thick photosphere, even at early times, indicating that the photospheric emission must peak in the FUV or even EUV. Darnley et al. went on to describe the extremely high velocity material (FWHM $\approx 13000\,\mathrm{km\,s^{-1}}$) seen fleetingly in the early-time (pre-maximum) spectra, described as "indicative of outflows along the polar direction—possibly highly collimated outflows or jets". There was also evidence for a mid-point (day 11) dip in the X-ray light curve across all three eruptions, which we will address further in Section 6.4. Darnley et al. ended on a prediction for the 2016 eruption occurring in mid-September (±1 month).

The *HST* observations of the 2015 eruption were successful in tying down a number of the outstanding 'unknowns' about the system. The NUV spectra (taken 4 and 5 days post-eruption) finally constrained the extinction toward the system, but otherwise revealed very limited features. The FUV spectrum, taken 3.32 days post-eruption was much more fruitful. Darnley et al. (2017b) reported that the FUV spectrum was broadly consistent with that expected from a CO WD (see, e.g., Shore, 2012) and importantly there was no evidence for any neon in the ejecta at that time. The FUV lines also exhibited very high velocities and the resonance lines remained optically thick (and saturated in some cases), the profile of the N v line (the highest ionisation energy line observed) was shown to be consistent with optically thick outflows or jets.

Newly obtained *HST* optical–NUV photometry was used to explore the late-decline and was coupled with archival observations to explore the quiescent system. Darnley et al. (2017a) found that 12a takes only ~ 75 days to reach quiescence following an eruption, showing a possible increase in luminosity toward the onset of the next event. The quiescent photometry were used to model the accretion disk (see, e.g., Godon et al., 2017), with those models indicating an extremely high $\dot{M}$. By extrapolating the quiescent disk models back to the late-decline, and with comparison to a late-time Keck spectrum of the 2014 eruption, Darnley et al. (2017a) presented evidence for the 12a accretion disk surviving each eruption and possibly dominating the optical–NUV flux as early as the plateau phase. The quiescent accretion rates presented were in the region of $(0.6 - 1.4) \times 10^{-6}\,\mathrm{M_\odot\,yr^{-1}}$ – once the additional effects of a considerable disk wind/outflow had also been considered (see, e.g., Matthews et al., 2015).

With the assistance of the PHAT survey team (Williams et al., 2014a), Darnley et al. (2017a) recovered the mass donor, an M 31 'red clump' star, most likely a low-luminosity red giant — with the donor constrained a limit could also be placed on the orbital period ($\gtrsim 5$ days). That paper concluded by assessing all the parameters of the system and made a *conservative estimate* of the time remaining for the WD to reach the Chandrasekhar mass of < 20 kyr.

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[14] `https://www.aavso.org`

[15] `https://www.britastro.org`

[16] `http://vsolj.cetus-net.org`

[17] Due to unfortunate weather conditions around the globe, none of the late-time spectroscopy was possible. This was all rescheduled for the 2016 eruption and those data remain under analysis.

[18] The *Swift* observations were hampered by a longer data retrieval time and were received and processed after the LCO data.

Table 5: Key parameters of the M31N 2008-12a system.

Parameter	Value	References
P_{rec}	347 ± 10 days	1
M_{WD}	$\simeq 1.38\,\mathrm{M}_{\odot}$	2
$\dot{M}_{\mathrm{SSS}}{}^{a}$	$1.6 \times 10^{-7}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$	2
$\dot{M}_{\mathrm{disk}}{}^{b}$	$(6 - 14) \times 10^{-7}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$	3
$M_{\mathrm{ejected,H}}$	$(0.26 \pm 0.04) \times 10^{-7}\,\mathrm{M}_{\odot}$	4
η^{c}	$+63\%$	2
L_{donor}	$103^{+12}_{-11}\,\mathrm{L}_{\odot}$	3
R_{donor}	$14.14^{+0.46}_{-0.47}\,\mathrm{R}_{\odot}$	3
$T_{\mathrm{eff,donor}}$	4890 ± 110 K	3
P_{orb}	$\gtrsim 5$ days	3
d	752 ± 17 kpc	5
$E\,(B - V)$	0.10 ± 0.03	6

[a] Derived by modelling the SSS development of M31N 2008-12a, it is assumed to be constant throughout a complete eruption cycle.
[b] Derived by fitting accretion disk models to the optical and UV quiescence SEDs. Here, the range during quiescence is presented.
[c] WD accretion efficiency; as $\eta > 0$, M_{WD} in increasing.
References — (1) Henze et al. (2015a, 2018), (2) Kato et al. (2015), (3) Darnley et al. (2017a), (4) Henze et al. (2015b), (5) Freedman et al. (2001), (6) Darnley et al. (2017b).

The observations of the 2015 eruption (Darnley et al., 2016a, 2017a,b) allowed us to complete the basic picture of 12a, placing numbers or strong constraints on most of the key system parameters, which are summarised in Table 5. A few gaps remained, including the 2010 eruption!

With a hole in the eruption history, an archival search for the 'missing' 2010 eruption was undertaken. It did not take long to find the culprit contained within a pair of observations taken on Nov 20, right in the PTF coverage gap (Henze et al., 2015a). The timing of the 2008–2014 events suggested that eruptions occurred slightly earlier each year — i.e. a recurrence cycle just under one year (see Figure 4). However, when the archival X-ray eruptions from 1992, 1993, and 2001 were included they appeared to break this pattern. The simplest solution to this apparent problem was a shorter recurrence period, half that observed between 2008–2014. Henze et al. (2015a) therefore adopted $P_{\mathrm{rec}} = 175 \pm 11$ days. Under this scenario, each of the observed eruptions in 2008–2014 was the second eruption that calendar year, the earlier eruption happened during the M 31 Sun constraint. But as the proposed P_{rec} was still just under six months, the eruptions would still creep earlier each year — following the 2015 eruption, Darnley et al. (2016a) predicted that by 2020/21 there would be a good probability of detecting the earlier eruption and confirming the six month cycle. However, if the eruption pattern remained unchanged, it would be substantially longer until a six month cycle could be confidently excluded.

6.4. The 'peculiar' 2016 eruption

The lead-in to 2016 focussed on a dedicated attempt to detect the 'early' eruption (*confidentially* predicted for 2016 March 23 ± 1 month; see Henze et al., 2019). The results of that work will be published in due course in Henze et al. (2019), but, it would not be considered a 'spoiler' to report here that the early 2016 eruption was (despite the heroic efforts of some of the observers involved) not recovered.

While the existence of the 'early' eruption remained unproved, attention was focussed to the 'normal' later-year event, and again a global detection effort was employed. The mid-September prediction came and went, as did the extended window (ending on October 13; Darnley et al., 2016a). The 2016 eruption finally occured on December 12 (Itagaki et al., 2016). The results of the 2016 eruption campaign are presented in full detail in Henze et al. (2018). In general, despite its lateness, the 2016 eruption proceeded largely as those preceding it, and with the earliest spectrum yet obtained, even stronger evidence of the short-lived high-velocity outflows or jets were seen. However, the 2016 eruption differed from its forerunners in two aspects.

Firstly, Henze et al. revealed a short-timescale cusp-like peak that preceded and outshone the 'normal' eruption peak (at day 1). While the paper discusses possible links between this cusp and the delayed eruption, it was noted that the timing of the 2016 cusp was coincident with holes in the light curves from 2013–2015 — so no strong connection could be made to the delayed eruption. The 2010 detection provided limited evidence for a similar event that year; an eruption otherwise deemed 'typical' (Henze et al., 2015a).

Secondly, the SSS phase, which in 2013–2015 had continued until day 18–19 post-eruption, began to turn-off at day 11 and was last detected by *Swift* on day 14 (Henze et al., 2018). Prior to turn-off, the unveiling of the 2016 SSS proceeded in a similar manner to that in 2013–2015, that and the similarity in the optical behaviour (sans the 'cusp') strongly implied that the eruptions themselves were similar — a similar ejected mass, with a similar velocity, and a similar peak luminosity, therefore a similar ignition (or accreted) mass must have been involved. How could a late eruption generate essentially a 'normal' eruption but a truncated SSS phase? The inter-eruption period of 12a had always varied, but the SSS phase had been consistent.

Given the generally low ejected mass and $\dot{M}$ of novae (see, e.g., Yaron et al., 2005), M_{WD} must be approximately constant between successive eruptions (whether long-term M_{WD} increases or decreases) and hence successive eruptions would always have the same ignition mass and similar eruptions. The logical explanation of a late eruption is a decrease in the average inter-eruption $\dot{M}$. This in turn would lead to a less massive accretion disk. A less massive disk would be more readily disrupted during an eruption. Henze et al. also noted that the 2016 eruption began to turn off (at day 11) at around the same time as the X-ray light curve dip seen in 2013–2015. Therefore it was proposed that day 11 was the natural turn off time of the SSS in 12a, given the ignition mass. The higher average $\dot{M}$ in 2013–2015 meant the disk was minimally disrupted, allowing accretion on the WD to resume once the surface nuclear burning first began to wane (at around day 11), the availability of additional H-rich fuel artificially extended the SSS-phase by a week or so. Henze et al. proposed that in 2016 a less massive disk was more substantially disrupted and accretion onto the WD only resumed once the nuclear burning had ceased. In making this proposal, Henze et al. strongly recommended further study of this ‘re-feeding’ concept. Subsequently, Aydi et al. (2018a) suggested that SSS re-feeding might explain the unexpected longevity of the SSS phase in the recent nova V407 Lupi.

Following 2016, the eruption pattern proposed in Henze et al. (2015a) had been thrown into disarray. Was the 2016 event a statistical anomaly, or was the assumed model incorrect? Moreover, what had caused the decreased $\dot{M}$ between the 2015 and 2016 eruptions, which must have dropped by $\sim 25\%$ from the ‘norm’ during this period?

6.5. *2017 and 2018 — back on track?*

It is fair to write that we really weren’t sure when to expect the 2017 eruption, with predictions from within the ‘12a collaboration’ ranging from the normal pattern to a T Pyxidis-style subsidence (Schaefer, 2010; Godon et al., 2018). It was not even certain that the ‘2017 eruption’ (aka the next eruption) would occur in 2017.

Leaving it very late, the 2017 eruption was detected on December 31.77 UT[19] at the West Challow Observatory in the UK (Boyd et al., 2017). The 2018 event, was less suspenseful, and was detected on November 6 by the LT (Darnley et al., 2018). In Table 6 we provide a summary of the past 14 detected eruptions of 12a (based on similar Tables in Darnley et al., 2017a,b).

In Figure 4 we show (left-hand panel) the original 12a eruption ‘model’ (Henze et al., 2015a) that was consistent with either a ~ 6 month or ~ 12 month $P_{\rm rec}$ and described the 2008–2015 eruption timings reasonably well. But with the inclusion of the 2016–2018 eruptions, which possibly also emphasise the 2013 event, it seems clear that this original model does not well describe the eruptions. In the right-hand panel, we show the distribution of inter-eruption gaps. The solid blue line shows the mean, 360 days, the red-dashed line the median, 347 days, the standard deviation is 50 days. If we are concerned with how well the mean inter-eruption time is known, then $\overline{P_{\rm rec}} = 0.99 \pm 0.02$ years[20].

The 2017 and 2018 eruptions will be presented in a joint paper (Darnley et al., 2019a) — both eruptions appear, at least superficially, to be very similar to the 2013–2015 events. And, so as not to break with tradition, in terms of predictions for the 2019 eruption, then at the time of writing, we would expect it to occur 360 ± 50 days after the 2018 event: between September 12 and December 21.

Table 6: Summary of the 14 observed eruptions of M31N 2008-12a.

Eruption date† [UT]	Inter-eruption timescale [days]‡	References
(1992 Jan. 28)	. . .	1, 2
(1993 Jan. 03)	341	1,2
(2001 Aug. 27)	. . .	2, 3
2008 Dec. 25	. . .	4
2009 Dec. 02	342	5
2010 Nov. 19	352	2
2011 Oct. 22.5	337.5	6
2012 Oct. 18.7	362.2	7
2013 Nov. 26.95 ± 0.25	403.5	4, 8, 9
2014 Oct. 02.69 ± 0.21	309.8 ± 0.7	10, 11
2015 Aug. 28.28 ± 0.12	329.6 ± 0.3	12
2016 Dec. 12.32 ± 0.17	471.7 ± 0.2	13
2017 Dec. 31.3 ± 0.1	384.0 ± 0.2	14, 15
2018 Nov. 06	∼ 310	15, 16

Updated version of Table 1 from Darnley et al. (2017a,b).
†Those in parentheses are extrapolated from X-ray data.
‡Only quoted for consecutive detections in consecutive years.
References — (1) White et al. (1995), (2) Henze et al. (2015a), (3) Williams et al. (2004), (4) Nishiyama & Kabashima (2008), (5) Tang et al. (2014), (6) Korotkiy & Elenin (2011), (7) Nishiyama & Kabashima (2012), (8) Darnley et al. (2014b), (9) Henze et al. (2014a), (10) Darnley et al. (2015), (11) Henze et al. (2015b), (12) Darnley et al. (2016a), (13) Henze et al. (2018), (14) Boyd et al. (2017), (15) Darnley et al. (2019a), (16) Darnley et al. (2018).

6.6. *The super-remnant*

We continue to investigate archival observations to attempt the recovery of past – missed – eruptions. Our key collaborator, Allen Shafter, alerted us to a Hα image of the 12a field that he and Karl Misselt had taken using the Steward 2.3m Bok Telescope (see Coelho et al., 2008; Franck et al., 2012) as part of an earlier M 31 nova survey. These data did not reveal a previous eruption, but they did show evidence for *vastly* extended nebulosity around 12a (Darnley et al., 2015). This discovery was soon confirmed via narrowband data from LGGS (Massey et al., 2007) and the LT. Fortuitously, the LT SPRAT (see Piascik et al., 2014) long-slit spectra of the 2014 eruption contained Hα+[N II] and [S II] emission (but little else) from a bright knot in this nebula (Darnley et al., 2015).

To follow-up, high-spatial resolution Hα+[N II] imaging was obtained with *HST*, and deep low-resolution spectroscopy from the Gran Telescopio Canarias and HET. *HST* imaging clearly revealed the shell-like nature of the nebula with the spectra confirming that the phenomenon was not a SN remnant, yet was consistent with being predominately swept-up ISM (Darnley et al., 2019b), see Figure 5.

With semi-major and -minor axes of 67 and 45 pc, respectively, and a swept-up mass of $\sim 10^{5-6}\,{\rm M}_\odot$ (Darnley et al., 2015, 2019b), a serious question remained, could sustained RN eruptions produce such a vast structure?

The expanding nebulosity around the Galactic nova GK Persei was first noted by Ritchey (1901a,b), with that

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[19] The time recorded in Table 6 is the estimate of eruption itself.

[20] The authors agonised about whether to comment on this number, but decided to leave any speculation to the reader.

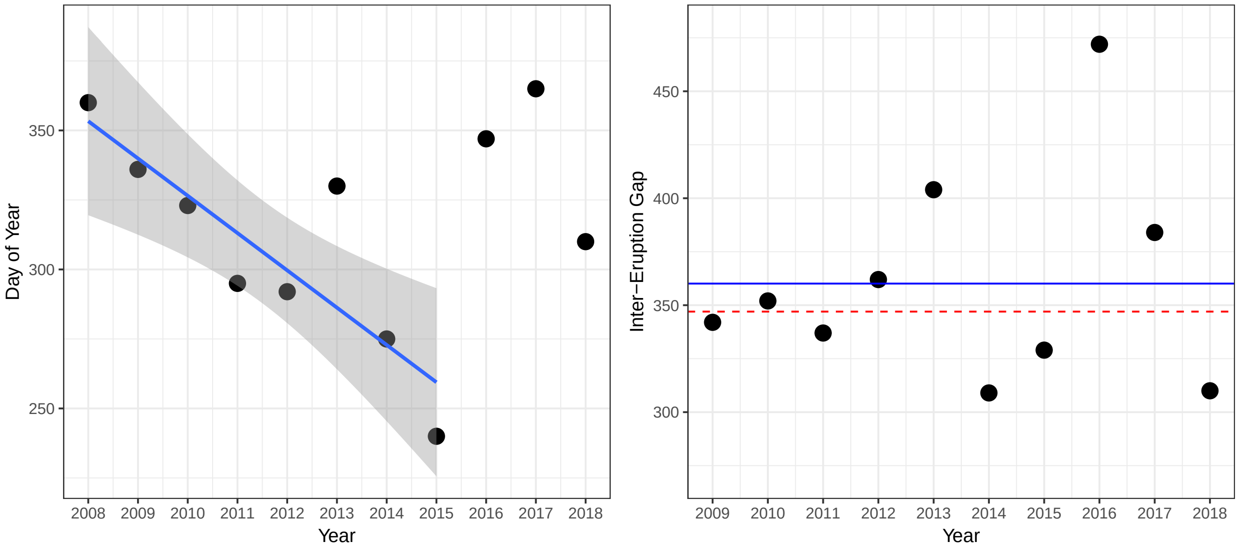

Figure 4: (Left) Distribution of M31N 2008-12a eruption dates since 2008, the blue line and the grey shaded region indicate the original timing model (Henze et al., 2015a). (Right) Distribution of 12a inter-eruption gaps, the blue line shows the mean, the red-dashed line the median.

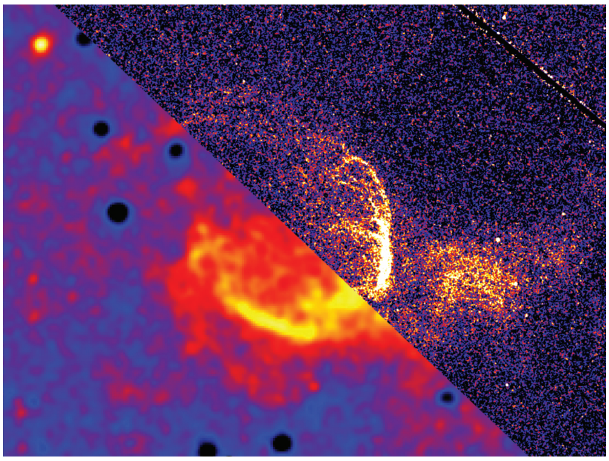

Figure 5: The nova super-remnant surrounding M31N 2008-12a. The lower left of the image shows the LT ground-based narrow-band Hα data, the upper right the high spatial resolution *HST* Hα+[N II] imaging. Here the colour-scale is based on brightness, this image has been recreated based on the data published in Darnley et al. (2019b).

nova's ejecta first photographed by Barnard[21] in 1916 (see Bode & Evans, 2008). Nebular ejecta have been discovered and investigated around $\sim 10\%$ of Galactic novae (see, for e.g., Wade, 1990; Slavin et al., 1995; Bode et al., 2007), but the largest of these are less than a parsec across (Bode et al., 2004; Shara et al., 2007, 2012). Evidence for interacting ejecta from successive RN eruptions has been presented for T Pyxidis (Shara et al., 1997; Toraskar et al., 2013).

As a proof of concept, Darnley et al. (2019b) presented a hydrodynamical simulation (based on the `Morpheus` code; Vaytet et al., 2007) of 100,000 annual eruptions of 12a. This simulation followed each set of ejecta separately, including their self-interaction and interaction with the surrounding ISM. Darnley et al. showed that such recurrent eruptions create a vast evacuated region around the central system while 'piling' up the ISM in a thick expanding shell. Unlike remnants of single explosions/eruptions, this 'super-remnant' contained a continually shock-heated region, inside the outer shell, where ejecta from successive eruptions collide. The properties of the simulated super-remnant were consistent with the observational constraints. Given the observed size of the super-remnant, Darnley et al. suggested an age of 6×10^6 yrs: assuming $\dot{M} = 1.6 \times 10^{-7}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ (Kato et al., 2015), an accretion efficiency of only $\approx 40\%$ would be required to grow a WD from $1\,\mathrm{M}_\odot$ to very close to the Chandrasekhar mass in that time.

At the time of writing, the authors see no reason why similar or 'natal' super-remnants should not surround all RNe, particularly those with the shortest inter-eruption periods. However, given their vast scale and expected low surface brightness ($m_{\mathrm{H}\alpha} \gtrsim 24\,\mathrm{arcsec}^{-2}$) searches for additional examples are perhaps best conducted extragalactically. The existence of super-remnants around near-Chandrasekhar mass, rapidly accreting, WDs has potentially interesting consequences for any catastrophic event that may subsequently befall the central system. For example, the interaction of a SN Ia explosion with a super-remnant environment should be explored to identify potential observational signatures for the nova pathway to a SN Ia.

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[21] Who identifies a "Miss (Vera Marie) Gushee" as the photographer.

7. Open questions for the next few decades

Numerous questions about novae still require answers. Those related to ISM enrichment, γ-rays, dust formation, and the ejecta geometries are probably best broached Galactically. But when it comes to populations and the link to SNe Ia, extragalactic work is vital. Are the faint–fast novae related to the RNe, are they all RRNe? How large is the RRN population, are systems like M31N 2008-12a rare, or is 12a the tip of the iceberg? Can (or should) the MMRD concept be salvaged? Do RRNe provide a substantial SN Ia channel? What is the ratio of CO to ONe WDs in novae? Does the nova population vary between and within host galaxies? Do local stellar population, star formation history, and metallicity affect novae? How do novae affect their environment, is the 12a nova super-remnant unique?

The hugely anticipated high-cadence all-sky surveys, such as LSST, could be a game changer, particularly for the faint–fast and RRNe (although the anticipated LSST observing cadence might be an issue). When launched, the *James Webb Space Telescope* could revolutionise the IR studies of novae and their ejecta, but we may also lose *HST* and its unparalleled UV capability. Novae will have to compete for their share of new facilities, and while discovery of new novae is one thing, follow-up capability is another. But despite the onslaught of automated all-sky surveys, it was the amateur community that discovered 12a and continues to provide invaluable support to its study. A huge proportion of extragalactic nova discoveries still come from amateur astronomers, these individuals and groups must not be under-valued. The future is bright, we have a lot of work still to do, observational nova work is likely to become more rewarding, but much more challenging.

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