

M31N 2008-12a — The Remarkable Recurrent Nova in M31

M. J. Darnley¹

¹*Astrophysics Research Institute, Liverpool John Moores University, IC2
Liverpool Science Park, Liverpool, L3 5RF, UK; m.j.darnley@ljmu.ac.uk*

Abstract. M31N 2008-12a is a remarkable recurrent nova within the Andromeda Galaxy. With eleven eruptions now identified, including eight in the past eight years, the system exhibits a recurrence period of one year, and possibly just six months. This short inter eruption period is driven by the combination of a high mass white dwarf ($1.38 M_{\odot}$) and high mass accretion rate ($\sim 1.6 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$). Such a high accretion rate appears to be provided by the stellar wind of a red giant companion. Deep $H\alpha$ observations have revealed the presence of a vastly extended nebula around the system, which could be the ‘super-remnant’ of many thousands of past eruptions. With a prediction of the white dwarf reaching the Chandrasekhar mass in less than a mega-year, M31N 2008-12a has become the leading pre-explosion type Ia supernova candidate. The 2016 eruption – to be the twelfth detected eruption – is expected imminently, and a vast array of follow-up observations are already planned.

1. Introduction

Novae are powered by a thermonuclear runaway occurring at the base of an accreted layer at the surface of a white dwarf (WD). A sub-class of the cataclysmic variables (CVs), novae occur in close binary systems where the WD accretes material from its companion, usually via an accretion disk around the WD. Classical Novae have been observed in eruption only once, whereas the Recurrent Novae (RNe) have been detected erupting at least twice and have observed recurrence periods up to ~ 100 years. Such short recurrence periods are driven by the combination of a high mass WD and a high mass accretion rate (see Bode & Evans 2008; Bode 2010; Darnley et al. 2012; Woudt & Ribeiro 2014, for recent reviews). RNe have long been a proposed single-degenerate pathway to Supernovae Type Ia (SNe Ia), with recent works indicating that the WD mass in nova systems may indeed be growing over time (e.g. Hillman et al. 2016).

The remarkable M31N 2008-12a was first observed in eruption in 2008 (Nishiyama & Kabashima 2008). Since then, eruptions have been discovered in each year, the most recent in 2015 August – indicating a mean recurrence period of 347 ± 10 days (Darnley et al. 2016a). However, when archival X-ray detections of eruptions from 1992, 1993, and 2001 (Henze et al. 2014) are also considered, there is strong evidence that the true recurrence period may be half as long, 174 ± 10 days (Henze et al. 2015a).

In this article, we review a number of the most interesting and unusual features of the M31N 2008-12a system. However, we also refer the reader to the extensive published work on this system (see Darnley et al. 2014, 2015, 2016a; Henze et al. 2014, 2015a,b; Kato et al. 2015, 2016; Tang et al. 2014).

2. The white dwarf

With such a short recurrence period, the inference is that the WD in the M31N 2008-12a system must be high, and probably the highest mass WD yet found in a CV. The rapid unveiling of the super-soft source (SSS) X-ray emission after each eruption – just six days (Darnley et al. 2016a) – points to a low ejected mass ($\sim 3 \times 10^{-8} M_{\odot}$; Henze et al. 2015a); the short duration of the SSS ($t_{\text{off}} \approx 19$ days) again indicates a high mass WD. Modelling of the 2013 eruption by Tang et al. (2014) suggested that $M_{\text{WD}} > 1.3 M_{\odot}$ and that the accretion rate must be $> 1.7 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. Subsequent treatments by Kato et al. (2015), using data from multiple eruptions and assuming a recurrence period of one year, are consistent with $M_{\text{WD}} = 1.38 M_{\odot}$, $\dot{M} = 1.6 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, and a mass accumulation efficiency of $\eta = 0.63$. Both the Tang et al. (2014) and Kato et al. (2015) works indicate that the WD in M31N 2008-12a will reach the Chandrasekhar mass (M_{Ch}) in less than 1 Myr.

With the mass of the WD increasing, the ultimate fate of the system will therefore depend upon the underlying composition of that WD. An ONe WD will be expected to form a neutron star when M_{Ch} is reached, only a CO WD will explode as a SN Ia. However, in either situation, M31N 2008-12a is still of vital importance, being so close to M_{Ch} it is either the leading candidate for either an accretion induced collapse or a SN Ia. The recent work of Hillman et al. (2016) has shown that a CO WD can grow from its formation mass ($< 1.1 M_{\odot}$) to M_{Ch} via a long series of H-flashes (novae) interspersed with He-flashes (He-novae) with little or no tuning of the system parameters or accretion rate. That work, the discovery of M31N 2008-12a, and recent RN population work (Pagnotta & Schaefer 2014; Shafter et al. 2015; Williams et al. 2016) has significantly strengthened the case for novae contributing to the SN Ia progenitor population.

3. The system

The high mass accretion rates in RNe are typically provided by either a Roche lobe overflowing sub-giant, as in the U Scorpii system, or via the stellar wind of a red giant donor (e.g. RS Ophiuchi; Darnley et al. 2012). Using the *Hubble Space Telescope* (HST) Bode et al. (2009) and Williams et al. (2016) have shown that quiescent novae with red giant donors (near-infrared observations) or luminous accretion disks (visible and near-ultraviolet) can be directly imaged at the distance of M31. Both Darnley et al. (2014) and Tang et al. (2014) reported the detection of M31N 2008-12a at quiescence using archival HST observations. The SED obtained from those visible and NUV images indicated the presence of an extremely luminous accretion disk, however, the NIR data were too crowded to usefully constrain the donor.

Although the eruptions of M31N 2008-12a have been followed photometrically from peak back to quiescence (Darnley et al. 2016b), to date we have only been able to follow the eruptions spectroscopically for the first five days post-eruption. Darnley et al. (2016a) compiled the spectra from the 2012–2015 eruptions and derived the ejecta expansion velocity as a function of time since each eruption. This was conducted by using the FWHM of the $H\alpha$ emission lines as a proxy of the expansion velocity in the radial direction to the observer. This analysis clearly indicated that the ejecta velocity decreased as a function of time with $v \propto t^{-1/3}$, consistent with Phase II shock behaviour (adiabatic expansion, e.g. Bode & Kahn 1985) as the M31N 2008-12a ejecta interact with surrounding, pre-existing, and nearby material. With eruptions occurring regularly

in the system, any such circumbinary material must be replenished in between each eruption.

The majority of the spectra taken of M31N 2008-12a to-date have been at low-resolution, as somewhat necessitated by the faintness and distance of the system. Darnley et al. (2016a) also presented a co-added spectrum combining all data from the 2012–2015 eruptions. This deep spectrum indicated the presence of coronal [Fe VII], [Fe X], and [Fe XIV] emission lines as are typically associated with shocks between a nova ejecta and surrounding material. The deep spectrum also contained an emission band at $\sim 6830 \text{ \AA}$ that is consistent with Raman scattering of the O VI resonant doublet (at 1032/1038 \AA). Such Raman scattered features are common in the spectra of symbiotic stars.

Together, the combination of the spectral line development, the coronal emission lines, the Raman emission band, and also the photometric behaviour of each eruption (see Darnley et al. 2016a), provide compelling evidence as to the nature of the mass donor in the system – all pointing to a red giant, and wind accretion. This in itself poses an intriguing thought, with the orbital period of novae with red giant donors being of order a year (Darnley et al. 2012), M31N 2008-12a is the only known nova whose orbital period is approximately the same as its recurrence period. Somero et al. (2016) have recently indicated that the red giant donor in the RS Oph system may be tidally locked to its WD and hence the orbits circularised. Any deviation from circular orbits in the M31N 2008-12a system however, may lead to an accretion rate, and hence inter eruption interval, that is affected by the orbital phase.

Darnley et al. (2016a) also discussed the accretion disk around the WD, and considered the possibility that the disk survives each eruption. With a short inter eruption period it is fair to assume that accretion must begin shortly after each eruption. Schaefer et al. (2011) argued that the formation timescale of an accretion disk must be at least one orbital period of the system. Therefore, with a red giant donor, and the recurrence period in M31N 2008-12a of order the orbital period, it seems unlikely that the disk seen in the HST observations (Darnley et al. 2014; Tang et al. 2014) could re-form in such a short timescale – therefore the disk must survive. The accretion disk, and its survival, will be discussed in further detail in Darnley et al. (2016b).

4. The ‘super remnant’

With one or even two eruptions every year since at least the early 1990s, the search is on to recover some of the missing eruptions. These efforts led to the discovery of extended $H\alpha$ emission around the nova within archival Steward Observatory (Coelho et al. 2008) and Local Group Galaxies Survey data (Massey et al. 2007). To confirm this emission, a series of deep $H\alpha$ observations were taken by the Liverpool Telescope (LT; Steele et al. 2004). Those observations uncovered a shell-like elliptical nebula centred on the position of the nova (see Figure 1 and Darnley et al. 2015). The nebula itself is vast, measuring over 130 pc along the major axis and 90 pc across the minor axis, and is somewhat larger than the majority of Galactic SN remnants.

A spectrum of the south-western ‘knot’ (see Figure 1) was serendipitously obtained by the long slit of the SPRAT (Piascik et al. 2014) instrument on the LT during the 2015 eruption (Darnley et al. 2015). That spectrum revealed only three sets of emission lines, $H\alpha$, [N II] (6548/6584 \AA), and [S II] (6716/6731 \AA), no [O III] emission was detected in the spectrum nor in narrow-band imaging (Massey et al. 2007). The

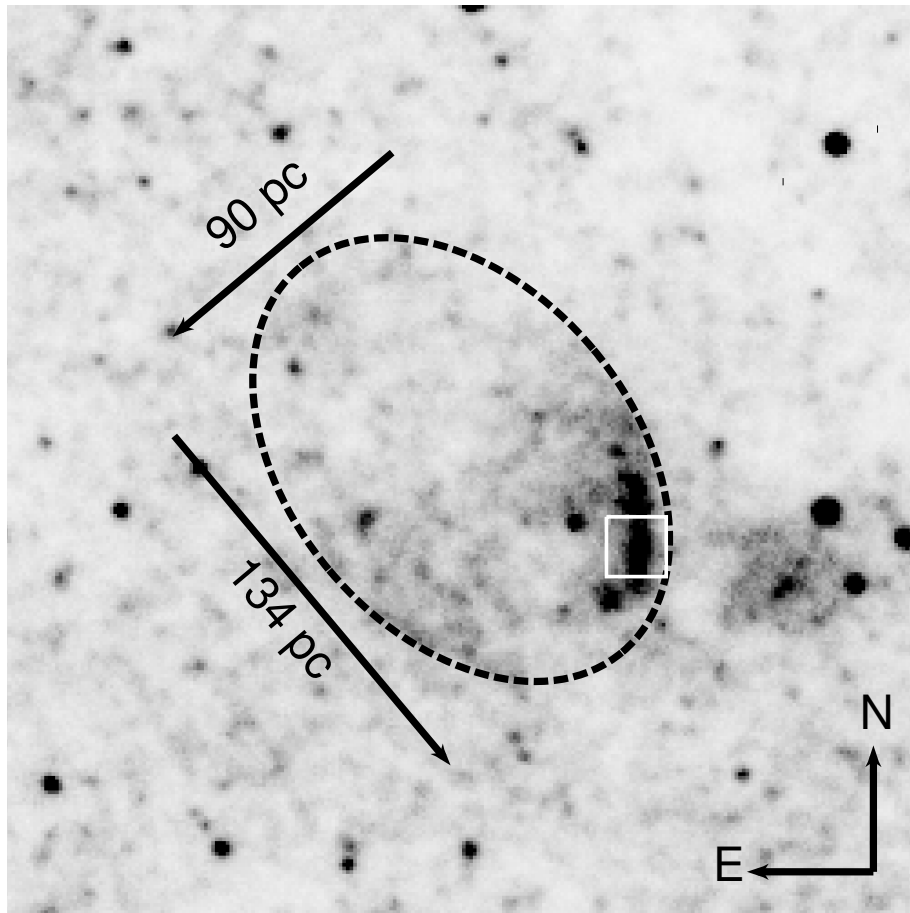


Figure 1. Liverpool Telescope 68.7 ks $H\alpha$ image (approximately $1'.5 \times 1'.5$) showing the region around M31N 2008-12a (centre of image). The dashed ellipse borders the elliptical nebulosity that surrounds the system – the proposed ‘super remnant’. The white box indicates the position of the south-western ‘knot’ (see text for further discussion).

$[S\ II]/H\alpha$ ratio of 0.35 is inconclusive as to the nature of the nebula, but the $[S\ II]$ doublet line ratio indicates an electron density that is consistent with the nebula mass being dominated by the ISM swept up from within the shell.

Darnley et al. (2015) proposed that the extended nebulosity is the ‘super-remnant’ of many thousands of past eruptions from M31N 2008-12a. Hydrodynamic simulations of the formation of such a phenomena are underway, support this hypothesis, and will be reported in a follow-up paper (Darnley & O’Brien 2016). Ten orbits of HST Cycle 24 time has been awarded to study the structure and possible formation pathway of the super remnant, with observations due to be taken in 2016 December.

5. Summary and the future

Based on the times of the last eleven observed eruptions, Darnley et al. (2016a) predicted that the next observable eruption of M31N 2008-12a will take place between 2016 August 21 and October 13 (1σ range). A global network of observers has been established to detect this eruption in order to ensure early discovery and the triggering of follow-up observations. At the time of writing (2016 October 13), this window has now passed without an eruption¹. When the next eruption is detected, a range of follow-up programmes will be triggered including late time spectroscopy (beyond the 5 day limit so far achieved). These include observations from Gemini North, Gran Telescopio Canarias (GTC), Hobby Eberly Telescope (HET), and the Large Binocular Telescope (LBT). In addition to late time spectroscopy of the eruption, they will each obtain deep spectra of the proposed super-remnant, and will attempt spectroscopy at quiescence (a first beyond the Galaxy and Magellanic Clouds).

M31N 2008-12a is a truly remarkable system, with observed eruptions yearly and a possible six months recurrence period. The WD in the system is close to the Chandrasekhar mass limit, the accretion rate is high, most likely fed by the stellar wind of a red giant, and the accretion disk appears to survive each eruption. The system is also surrounded by a huge region of extended nebulosity, which has been proposed to be the super-remnant of many thousands of past eruptions. The one big outstanding question is the composition of the WD itself, but nevertheless M31N 2008-12a has become the leading pre-explosion SN Ia progenitor candidate. If confirmed, the super-remnant phenomena may exist around all RNe and could provide an invaluable ‘sign post’ around exploding SNe Ia pointing directly to the progenitor type.

The 2016 eruption is due imminently (Darnley & Henze 2016), we welcome and encourage all observations of this and future eruptions.

Acknowledgments. This article is presented on behalf of the ‘12a’ collaboration. M.J.D. would like to particularly thank Martin Henze for his invaluable help in our on-going campaigns with this remarkable system, and also the LOC and SOC for organising such a wonderful workshop.

References

- Bode, M. F. 2010, *Astronomische Nachrichten*, 331, 160. 0911.5254
 Bode, M. F., Darnley, M. J., Shafter, A. W., et al. 2009, *ApJ*, 705, 1056. 0902.0301
 Bode, M. F., & Evans, A. (eds.) 2008, *Classical Novae*, 2nd Edition, vol. 43 of Cambridge Astrophysics Series (Cambridge: Cambridge University Press)
 Bode, M. F., & Kahn, F. D. 1985, *MNRAS*, 217, 205
 Coelho, E. A., Shafter, A. W., & Misselt, K. A. 2008, *ApJ*, 686, 1261. 0807.0210
 Darnley, M. J., & Henze, M. 2016, *The Astronomer’s Telegram*, 9415
 Darnley, M. J., Henze, M., Bode, M. F., et al. 2016a, *ApJ*, in press, ArXiv e-prints. 1607.08082
 Darnley, M. J., Henze, M., Steele, I. A., et al. 2015, *A&A*, 580, A45. 1506.04202
 Darnley, M. J., Hounsell, R., Williams, S. C., et al. 2016b, in preparation
 Darnley, M. J., & O’Brien, T. J. 2016, in preparation
 Darnley, M. J., Ribeiro, V. A. R. M., Bode, M. F., et al. 2012, *ApJ*, 746, 61. 1112.2589
 Darnley, M. J., Williams, S. C., Bode, M. F., et al. 2014, *A&A*, 563, L9. 1401.2905
 Henze, M., Darnley, M. J., Kabashima, et al. 2015a, *A&A*, 582, L8. 1508.06205

¹It was hoped that the 2016 eruption would appear in time for this article.

- Henze, M., Ness, J.-U., Darnley, M. J., et al. 2014, *A&A*, 563, L8. 1401.2904
Henze, M., Ness, J.-U., Darnley, M. J., et al. 2015b, *A&A*, 580, A46. 1504.06237
Hillman, Y., Prialnik, D., Kovetz, A., et al. 2016, *ApJ*, 819, 168. 1508.03141
Kato, M., Saio, H., & Hachisu, I. 2015, *ApJ*, 808, 52. 1506.05364
Kato, M., Saio, H., Henze, M., et al. 2016, *ApJ*, 830, 40. 1607.07985
Massey, P., McNeill, R. T., Olsen, et al. 2007, *AJ*, 134, 2474. 0709.1267
Nishiyama, K., & Kabashima, F. 2008, CBAT. http://www.cbat.eps.harvard.edu/iau/CBAT_M31.html#2008-12a
Pagnotta, A., & Schaefer, B. E. 2014, *ApJ*, 788, 164. 1405.0246
Piascik, A. S., Steele, I. A., Bates, S. D., et al. 2014, *SPIE Conference Series*, 9147, 8
Schaefer, B. E., Pagnotta, A., LaCluyze, A. P., et al. 2011, *ApJ*, 742, 113. 1108.1214
Shafter, A. W., Henze, M., Rector, T. A., et al. 2015, *ApJS*, 216, 34. 1412.8510
Somero, A., Hakala, P., & Wynn, G. A. 2016, *MNRAS*, in press. 1610.00914
Steele, I. A., Smith, R. J., Rees, P. C., et al. 2004, in *Ground-based Telescopes*, edited by J. M. Oschmann, Jr., vol. 5489 *SPIE Conference Series*, 679
Tang, S., Bildsten, L., Wolf, W. M., et al. 2014, *ApJ*, 786, 61. 1401.2426
Williams, S. C., Darnley, M. J., Bode, M. F., et al. 2016, *ApJ*, 817, 143. 1512.04088
Woudt, P. A., & Ribeiro, V. A. R. M. (eds.) 2014, *Stella Novae: Past and Future Decades*, vol. 490 of *Astronomical Society of the Pacific Conference Series* (San Francisco: Astronomical Society of the Pacific)