Recurrent Novae — A Review

K. Mukai[1,2]

[1] *CRESST and X-ray Astrophysics Laboratory, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA*

[2] *Department of Physics, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA*

Corresponding author: Koji.Mukai@nasa.gov

Abstract

In recent years, recurrent nova eruptions are often observed very intensely in wide range of wavelengths from radio to optical to X-rays. Here I present selected highlights from recent multi-wavelength observations. The enigma of T Pyx is at the heart of this paper. While our current understanding of CV and symbiotic star evolution can explain why certain subset of recurrent novae have high accretion rate, that of T Pyx must be greatly elevated compared to the evolutionary mean. At the same time, we have extensive data to be able to estimate how the nova envelope was ejected in T Pyx, and it turns to be a rather complex tale. One suspects that envelope ejection in recurrent and classical novae in general is more complicated than the textbook descriptions. At the end of the review, I will speculate that these two may be connected.

Keywords: cataclysmic variables - symbiotic stars - recurrent novae - individual: T Pyx.

1 Introduction

Nova eruptions are understood to be powered by thermonuclear runaway (TNR) on the surface of accreting white dwarfs. Hundreds of objects in the Galaxy have been seen to experience one nova eruption: these are called classical novae (CNe). Recurrent novae (RNe) are objects that have been seen to experience multiple nova eruptions. There are currently 10 confirmed RNe in the Galaxy. Between 10^{-6} and 10^{-4} $M_\odot$ of hydrogen rich material needs to be accreted to reach the critical temperature and density required for TNR. The critical mass is lower for more massive white dwarfs with higher gravity. Therefore, we expect RNe to contain near Chandrasekhar mass white dwarf accreting at a high rate. This makes RNe candidate progenitors of Type Ia supernova. For this reason, and because the recurrent nature of these objects allows studies that one cannot undertake for CNe, RNe have become the subject of intensive study.

It is impossible to present a comprehensive review of RNe in the space allotted; for that, the readers are referred to Schaefer (2010) and Anupama (2013). In this review, I will present selected highlights from multi-wavelength campaigns on recent RN outbursts, highlighting the work of the E-Nova collaboration[1]. I will also include results on several CNe: some of these system may be unrecognized or unconfirmed RNe, and others provide a useful comparison. I will also present some

quiescent observations. I will discuss implications on the white dwarf mass, the ejecta mass, the quiescent accretion rate,and the evolutionary scenarios for RNe and CNe.

1.1 X-ray bursts: a cautionary tale

Although RNe provide a unique opportunity to compare multiple nova episodes and possibly to compare accreted vs. ejected mass, only a handful of eruptions are observed for each system. This is in stark contrast to the studies of X-ray bursts, which are TNRs on accreting neutron stars. For example, Linares et al. (2012) studied 398 X-ray bursts detected from the transient X-ray binary in the globular cluster, Terzan 5, as the accretion changed by a factor of $\sim$5. This allowed these authors to study the relationship between the persistent luminosity, the burst recurrence time and the burst fluence, and thereby test the theory of TNR on neutron stars. Unfortunately, analogous tests have not been possible yet in the case of RNe.

Yet, even in the case of X-ray bursts, puzzles remain (Galloway et al. 2008). One is the burst oscillations observed during the decay. The drifting period of burst oscillations reflect the spin period of the neutron star atmosphere, which changes as the atmosphere expands and then contracts during the course of a burst. The presence of the oscillations during the decay, however, requires inhomogeneous burning over the neutron star

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[1] https://sites.google.com/site/enovacollab/

surface, even though one might expect uniform burning at this stage. The other is that pairs of bursts can occur with very short (<10 min) recurrence times, much too short to have accreted sufficient fuel for a new burst, judging by the persistent X-ray luminosity. This requires a reservoir of unburnt fuel on or very near the neutron star surface.

Thus, our theoretical understanding of X-ray bursts appears incomplete. It may well be that the current theories of nova outbursts are equally incomplete regarding, e.g., the recurrence times of RNe.

2 Selected Recent Results

2.1 Ejecta geometry

Montez et al. (in preparation) have detected extended X-ray emission in the *Chandra* observations of RS Oph obtained in 2009 and 2011. These structures are well-separated from the central X-ray source in the E-W direction, and were seen to expand from 2009 to 2011. This X-ray emitting bipolar outflow appears to follow the same angular expansion curve inferred for radio and *Hubble Space Telescope (HST)* bipolar structures observed earlier. The implied current expansion velocity is very high (of order 4,000 $km\,s^{-1}$. One possible origin of the bipolar flow is that RS Oph produced a true, well-collimated, jet near the time of nova eruption. Another is that an initially spherical ejecta encountered an equatorial torus and slowed down except in the polar directions. Since RS Oph is an RN in a symbiotic binary, the wind of the giant mass donor is a potential source of such a torus (Mohamed et al. 2013).

However, similar shaping of the ejecta might also occur in cataclysmic variables (CVs), with a Roche-lobe filling mass donor on or near the main sequence. In a series of simulations of the 2010 eruption of U Sco by Drake & Orlando (2010), the accretion disk is destroyed by the blast wave. This interaction causes the ejecta to expand away from the orbital plane. One particular simplifying assumption used by these authors, that of a uniform density disk, is a cause for concern, and independent simulations are needed to confirm their results in general. Nevertheless, the possibility that disk-blast wave interactions create bipolar outflow should be kept in mind for all novae, whether the underlying binary is a symbiotic system or a CV.

The above-mentioned results on RS Oph and U Sco are both about the outflow during the most recent outbursts of RNe, and may apply to CNe as well. In contrast, one type of study unique to RNe is the analysis of light echoes produced by ejecta from previous outbursts, as Sokoloski et al. (2013) did for T Pyx. The arrangement of the echo location on the sky and the progression of echos from east to west suggest a ring-like structure from a previous outburst. The delay times

for echoes along the north-south axis suggest a distance of 4.8±0.5 kpc for T Pyx. Moreover, the time lags between different echoes suggest that the ring is inclined ∼30–40° relative to the plane of the sky. This is most likely to reflect the binary inclination, somewhat higher than values previously inferred for T Pyx. Regardless of the precise inclination angle, the very fact that an equatorial ring was formed by the ejecta is worth noting.

2.2 Novae in symbiotic systems

Four of the known Galactic recurrent novae are in symbiotic binaries: RS Oph, T CrB, V745 Sco, and V3890 Sgr. They are all S type systems: they have a normal red giant mass donor, an orbital separation of order 1 AU, and an orbital period of order 1–2 years. In the other subtype, the D (dusty) type, the mass donor is an AGB star; the D type systems have a much wider orbit than the S type systems. Before 2010, all known TNR events in symbiotic systems were either a very slow "symbiotic novae," or very fast RNe (Mikolajewska 2008). It is important to note that TNR can lead to a quasi-static configuration without explosive mass loss in symbiotic novae. Also noteworthy is the fact that the accretion rate is high enough in the 4 S type symbiotic systems to produce RNe. If we take 10^{-7} $M_\odot\,yr^{-1}$ as the typical wind mass loss rate of a normal red giant, then this implies either Roche-lobe overflow or a very efficient mechanism to capture the wind, such as wind Roch-lobe overflow (Mohamed & Podiadlowski 2010), although M giants in symbiotic binaries may have higher mass-loss rates (Seaquist & Taylor 1990).

In March 2010, a D-type symbiotic system, V407 Cyg, became a nova. It was noteworthy for being the first nova to be detected as GeV γ-ray source with *Fermi* LAT (Abdo et al. 2010); it was the subject of an intensive multiwavelength from radio to X-rays (Nelson et al. 2012; Chomiuk et al. 2012). The X-rays were predominantly from the shock between the nova blast wave and the wind of the Mira type mass donor; interestingly, V407 Cyg became X-ray bright after the GeV signal faded. The thermal emission from the flash-ionized AGB wind was the dominant source of radio signal. While we learned a lot about the nova event, we are left with one important question: how often does V407 Cyg experience nova eruptions? Is it an unrecognized RN, or are the eruptions much less frequent?

2.3 Long period CVs

Darnley et al. (2012) proposed to classify novae into red giant, sub-giant, and main sequence systems. The orbital periods of the "sub-giant" systems are in the range 10 hrs to 6 days. According to the Ritter & Kolb catalog Version 7.20 (Ritter & Kolb 2003), there are 46

systems (excluding one uncertain entry in the catalog) in this orbital period range. Of the confirmed RNe, V894 CrA, U Sco and CI Aql belong to this group, and a fourth, V2487 Oph, probably has an orbital period in this range.

The evolution of such long-period CVs has not been studied extensively to date, compared to those with periods under 10 hrs, for which the basic framework and much more have been established (Knigge et al. 2011). CVs with similarly long orbital periods include several novae not known to be recurrent (GK Per, V1017 Sgr), supersoft sources (e.g., MR Vel, CAL 83), and V Sge and other systems that may be related to supersoft sources. One possibility is that these systems are currently undergoing thermal timescale mass transfer (TTMT; Schenker et al. 2002) or did so in the past. The evolution of CVs with P>10 hrs should be studied further, and a search for additional nova outbursts of systems like GK Per may be worthwhile.

2.4 Quiescent X-ray observations
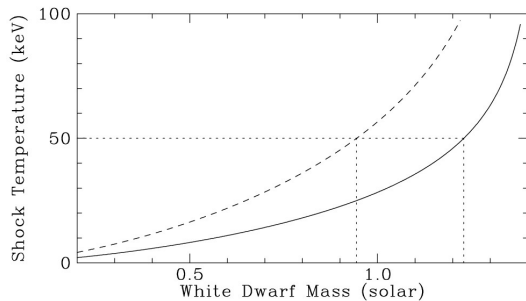
Figure 1: Possible white dwarf mass of V2487 Oph for the magnetic (dashed line) and the non-magnetic (solid line) cases

Of the known recurrent novae, T CrB and V2487 Oph are bright hard X-ray sources detected with *INTEGRAL* and with *Swift* BAT (see, e.g., Baumgartner et al. 2013). When such hard X-ray emission is detected, it can constrain both the white dwarf mass and the accretion rate in quiescence. In both magnetic and non-magnetic cases, hard X-rays are generated when the supersonic accretion flow encounters the white dwarf surface and is shock-heated. The hot plasma must radiatively cool before settling onto the white dwarf surface. In the case of magnetic CVs, the accretion flow is radial and its velocity is approximately at the free-fall value (Aizu 1973). The observed X-ray spectrum is multi-temperature in nature, with shock temperatures typically in the 10–50 keV range. The spectral curvature in the hard X-ray range is a reliable measure of the shock temperature, and can be used to infer the white dwarf mass (see, e.g., Yuasa et al. 2010). The situa-

tion may well be more complex for the boundary layer of non-magnetic CVs, but the maximum temperature is unlikely to exceed that expected for strong shocks from Keplerian velocity, and quiescent dwarf novae appear to follow the "Keplerian strong shock" relationship (Byckling et al. 2010).

Some authors have speculated that V2487 Oph may contain a magnetic white dwarf, based solely on its bright, hard X-ray emission. However, I measure a shock temperature of ∼50 keV using the BAT survey 8-channel spectrum, which corresponds to either a ∼0.9 $M_\odot$ magnetic white dwarf or a >1.24 $M_\odot$ non-magnetic white dwarf. Given the RN nature of this object, and given that repeated *XMM-Newton* observations have not revealed a spin modulation, the latter interpretation seems more likely.

2.5 High mass transfer rate: evolutionary or temporary?

Patterson et al. (2013) made the following simple prediction, based on average secular mass accretion rate: CVs above the period gap should experience nova eruptions once every 10,000 years or so, while those below the gap should recur once every 1 million year. For these normal CVs to be a RN, the accretion rate needs to be elevated by many orders of magnitudes above the secular mean. This is in contrast to the long-period systems with a sub-giant mass donor, where TTMT may drive a very high accretion rate. Similarly, in symbiotic systems, the mass loss rate from the donor is high enough, although the fraction that can be captured by the white dwarf is highly uncertain. Let us now consider the census of known classical and recurrent novae of various types with the above expectations in mind.

Among symbiotic stars, most novae are extremely slow and often referred to as symbiotic novae, the slowness suggestive of low-mass white dwarfs. The four well-known symbiotic recurrent novae are all in S-type systems: the short recurrence time and the high velocity of the ejecta both suggest these to have massive white dwarfs. The bifurcation of novae in symbiotic stars into two such extreme groups is very different from the situation in CVs, and should be investigated further. Although only a single outburst is known, the outburst properties of V407 Cyg makes it a candidate RN in this context. Since it is in a D type symbiotic system, with a much greater binary separation, an estimate of its quiescent accretion rate, when one is obtained, may tell us about how white dwarfs accrete in symbiotic stars, not to mention providing a clue as to its likely recurrence time.

U Sco, CI Aql, and V894 CrA are long-period systems; V2487 Oph may belong in this group, although its orbital period has not been determined yet. The TTMT

scenario points to the general framework for why these systems can be RNe. More research is needed to understand why some long-period systems are SSS, others RNe, and yet others CNe (as far as we know).

This leaves IM Nor (in the period gap) and T Pyx (below the gap) in the orbital period range with very low secular accretion rate and with only a small number of known classical novae (V1794 Cyg, V Per, ...). It is interesting to note that, while many classical novae are known above the gap (orbital period in the 3–10 hr range), no RNe are known in this regime. This could purely a matter of small number statistics. At the same time, it could be that the mechanism elevating the accretion rate of T Pyx and IM Nor far above the secular mean is much less effective for systems above the gap.

2.6 Multi-wavelength observations of T Pyx

Multi-frequency radio monitoring of novae is a powerful technique that allows us to estimate the total ejected mass in a relatively simple manner, although complications often arise (see, e.g., Roy et al. 2012 and references therein.) The nova ejecta is initially optically thick in the radio, thus the brightening traces the angular expansion of the ejecta. As the ejecta becomes optically thin, first from the highest frequencies then progressively to lower frequencies, this allows the amount of mass to be estimated, as long as we have a handle on the temperature and clumping of the ejecta. At the same time, we know that early X-ray emission from novae is likely due to shocks in the ejecta (e.g., O'Brien et al. 1994). With this mind, the E-Nova collaboration has begun multi-wavelength observations of recent novae using the much improved Karl G. Jansky VLA in the radio, and *Swift* and other observatories in the X-rays.

T Pyx is one of the major targets of the E-nova collaboration. The radio and X-ray results are presented by Nelson et al. (2014) and Chomiuk et al. (2014), respectively. T Pyx was largely undetected in the radio for the first $\sim$60 days since the discovery of the 2011 outburst, then started to rise around day $\sim$100. It was also X-ray faint during the first several months, and then started to rise slightly after the onset of the radio rise. The X-ray photons detected with *Swift* XRT are a mixture of optically thin emission from the shocked shell and the supersoft emission from the still nuclear burning surface. It is difficult to disentangle the two using short snapshot observations, hence it is difficult to determine, e.g., the turn-on time of the supersoft emission.

In the optical, T Pyx remained near peak optical magnitude for 2 or 3 months, depending on where one defines the peak to have ended and decline to have be-

gun. This implies a large photospheric radius, perhaps of order 5×10^7 km ($\sim$ a third of an AU; assuming a blackbody with a temperature of 10,000K, a distance of 4.8 kpc, and $A_V \sim 1.0$, this radius corresponds to a visual magnitude of V$\sim$7.9). This is well outside the central binary, yet it only takes of order 1 day for matter traveling at 600 km s^{-1} to reach this distance. For a shell at a distance of 1×10^8 km to have an optical depth of 1, which implies a column density of order 3 g cm^{-2} (assuming electron scattering dominates the opacity), the total mass of the shell must be greater than $\sim 5.0 \times 10^{-7}$ M$_\odot$. So the duration of optical peak implies either a continuous ejection of $\sim 5 \times 10^{-7}$ M$_\odot$ per day for several months, or that T Pyx went into a quasi-static, red giant-like configuration during the peak, and ejected the extended atmosphere with a significant delay. In the latter case, the total mass of the extended atmosphere must be much greater than 5×10^{-7} M$_\odot$, because it is a filled sphere and not a thin shell.

Schaefer et al. (2013) presented the detailed visual light curve of T Pyx during the initial rise. Until it reached V$\sim$7.7, it can be modeled well assuming a uniform expansion of the ejecta, then the observed brightness drops below this model. If we equate this instance with the time when the optical depth of the ejecta dropped below 1.0, we infer that an initial shell of $\sim 6 \times 10^{-7}$ M$_\odot$ was ejected.

Such a small ejection is easy to hide in the radio data, although there is one detection on day 17 that could be interpreted as due to this. On the other hand, continuous mass ejection of $\sim 5 \times 10^{-7}$ M$_\odot$ per day is difficult to reconcile with the deep radio non-detections followed by rapid brightening around day 60. Rather, the radio data are consistent with a prolonged period of quasi-stationary configuration, and a delayed ejection of a more massive (of order 10^{-5} M$_\odot$) shell. In addition, if the latter system was ejected with a larger velocity, then we expect shocked X-ray emission when it catches up with the initial ejecta. The existing X-ray data are broadly consistent with such a picture.

2.7 The cause of elevated mass transfer rate

For T Pyx, we have a clear-cut case that the mass transfer rate is elevated by several order of magnitudes above the evolutionary mean (Gilmozzi & Selvelli 2007). The same presumably applies to IM Nor as well.

Irradiation of the donor is often invoked as the explanation. However, theorists have long concluded that this requires hard photons, and therefore theoretical studies largely focus on X-ray binaries (see, e.g., Hameury et al. 1986; King 1989). To quote from Ritter (2000), "Energy emitted in certain spectral ranges,

as e.g., EUV radiation and soft X-rays, is unlikely to reach the photosphere of the donor." To reach the photosphere of K or M type dwarfs, irradiating flux needs to be able to penetrate above 10^{24} cm^{-2} of column, thus requiring strong flux above 10 keV. Therefore, supersoft sources or photospheric emission of otherwise very hot white dwarf only irradiates the chromosphere and above, and not the photosphere. The irradiation mechanism studied in above-mentioned papers cannot work when the irradiating flux is in the form of soft X-ray and EUV photons.

While V1500 Cyg is sometimes taken as an example of a system that is experiencing enhanced accretion rate due to irradiation, this is not necessarily the case. This is because one well-established effect of irradiation is to increase the luminosity of the existing structures, be it the secondary or the accretion disk. In fact, according to Somers & Naylor (1999), the elevated brightness of V1500 Cyg, which is currently an asynchronous polar due to its 1975 Nova eruption, is due to an orbitally modulated component, not due to the spin modulated component. Since accretion luminosity should be modulated on the spin period, we know that the extra light is due to the irradiated face of the secondary. In this picture, the reflection of the gradually decreasing post-nova white dwarf flux explains the secular changes in the brightness of V1500 Cyg, without invoking variable accretion rate.

Thomas et al. (2008) obtained phase-resolved K-band photometry of old novae of various ages since outburst. They were also able to interpret their results without invoking changing accretion rate. Rather, in their interpretation, variable irradiation, and hence variable reflection, changes the brightness of the existing structures, the accretion disk and the secondary. At a minimum, this points out that an enhanced brightness is insufficient to prove an enhanced accretion rate. These studies also suggest that irradiation by a post-nova does not lead to enhanced mass transfer, although they do not yet constitute a solid proof.

If not irradiation, what other mechanisms can potentially enhance the mass transfer? Here I speculate that the post-nova common envelope phase might be ultimately responsible, as follows.

The ring geometry of the ejecta of T Pyx (§2.1) suggests that the secondary plays a role in shaping the geometry of the ejecta. In symbiotic systems, slow novae can stay in the "plateau" phase for decades, whereas no such example is known among CVs, again implying that the secondary plays a role in ejecting the nova envelope. The potential role played by the common envelope system was first pointed out by MacDonald (1980) and later studied quantitatively by, e.g., Livio et al. (1990). The general consensus is that the common envelope phase can contribute to the ejection of the nova envelope, but only if the ejecta is moving more slowly than the orbital motion of the mass donor. The multi-wavelength data on T Pyx indeed suggests that the envelope may have been in a quasi-stationary configuration for 2–3 months, as it is for decades in slow symbiotic nova. The possibility that many novae in CVs may not be able to eject the bulk of the envelope, if it were not for the common-envelope phase, should therefore be investigated.

If common envelope phase is an important factor in the envelope ejection process, then this implies that the binary must have lost angular momentum. While the orbital period of T Pyx was seen to increase after the 2010 eruption (Patterson et al., this volume), the period increase only constrains the combination of ejected mass and angular momentum loss. If more than the minimum allowed mass was ejected, so was angular momentum. So the proposed scenario is that of a common-envelope interaction during the nova eruption, resulting in an impulsive angular momentum loss, which drives a higher accretion rate for the ensuing decades. I suggest that such a scenario deserves serious, quantitative analysis.

3   Summary and Conclusions

Recent RN eruptions have be subjected to intense multi-wavelength observing campaigns using advanced facilities, including the Karl G. Jansky VLA, many ground-based optical/IR telescopes, HST, *Swift* and other X-ray observatories. Although not a new discovery as such, recent images of nova ejecta demonstrates once again that they are not spherically symmetric. In the case of T Pyx, the multi-wavelength data strongly suggest that there was a initial, small ejection and a much larger, delayed ejection. These facts together suggest that the binary companion, via common-envelope interaction, may be involved in the ejection process.

It is expected that RNe harbor massive white dwarfs accreting at a very high rate. While the accretion rate may be high in some subset of RNe for evolutionary reasons (symbiotic RNe, and long-period systems), this is definitely not the case for T Pyx and IM Nor. Unfortunately, there is a serious difficulty with the commonly invoked mechanism of irradiation, when the irradiation is by soft X-ray and EUV photons. I presented a possible scenario involving impulsive angular momentum loss during the common envelope phase.

Acknowledgement

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DISCUSSION

CHRISTIAN KNIGGE: Regarding the possibility that irradiation might enhance the mass accretion rate: I think that an enhancement *is* possible, at least via irradiation-driven winds from the donor. In fact, this model was first proposed for SSS, where the irradiation is all in the soft X-ray/EUV regime.

KOJI MUKAI: It is true that the viability of irradiation-driven wind to enhance the accretion rate is a separate issue. I feel that sometimes the direct effect of irradiation is often too casually invoked as the explanation, and my intent was to advise caution.