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Radio studies of novae: a current status report and highlights of new results

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Abstract. Novae, which are the sudden visual brightening triggered by runaway thermonuclear burning on the surface of an accreting white dwarf, are fairly common and bright events. Despite their astronomical significance as nearby laboratories for the study of nuclear burning and accretion phenomena, many aspects of these common stellar explosions are observationally not well-constrained and remain poorly understood. Radio observations, modeling and interpretation can potentially play a crucial role in addressing some of these puzzling issues. In this review on radio studies of novae, we focus on the possibility of testing and improving the nova models with radio observations, and present a current status report on the progress in both the observational front and theoretical developments. We specifically address the issues of accurate estimation of ejecta mass, multi-phase and complex ejection phenomena, and the effect of a dense environment around novae. With highlights of new observational results, we illustrate how radio observations can shed light on some of these long-standing puzzles.

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1. Introduction

Novae occur in binary stellar systems where mass is transferred onto a white dwarf (WD) from either a main sequence, subgiant, or red giant companion. As the accreted material builds up on the WD surface, the temperature of the degenerate Fermi gas increases without any change of pressure. Ultimately, a thermonuclear runaway (TNR) ensues and subsequently the critical temperature is reached, breaking the degeneracy of the accreted layer and resulting in ejection of mass from the WD surface (see e.g. Starrfield, Iliadis & Hix 2008, also Starrfield 2012, this Volume). This event is observed as a nova — a sudden visual brightening at optical wavelengths. For more on the optical studies of novae, see the reviews by Anupama & Kamath (2012) and Shore (2012) in this Volume. Nova events are fairly common (∼35 novae per year in the Milky Way; Shafter 1997) and bright (sometimes even visible to the naked eye for days to weeks). Thus, novae provide valuable nearby laboratories for the study of nuclear burning and accretion phenomena. Additionally, if the ejected mass is less than that accreted since the last outburst, then nova-hosting WDs will grow in mass with time. This makes them interesting candidates for progenitors of Type Ia supernovae (SNe Ia). See Starrfield et al. (2004), della Valle & Livio (1996) and also Kato & Hachisu (2012; this Volume) for more details on the connection between novae and SN Ia progenitors.

Novae have been observed in detail for the greater part of the 20th century (e.g., Payne-Gaposchkin 1964), and the basics of nova theory have been established since the 1970s (e.g., Starrfield et al. 1972). One might therefore expect that we understand these common stellar explosions in depth, but many fundamentals remain poorly understood or observationally unconstrained. Some intriguing discrepancies exist between observations and theoretical predictions — like ejecta masses which are observed to be an order of magnitude larger than predicted by theory. In addition, observations indicate that nova explosions are complex, with multiple phases — and perhaps physical drivers — of mass ejection (Williams 2012). Models agree that material is not ejected from the WD surface in a single impulsive burst (Prialnik 1986), but the consistency of observed and predicted ejection histories has not been extensively tested. Radio observations are ideal for pursuing these issues, because they trace the majority of the ejected mass in a relatively simple and easily modeled fashion.

In this review, we summarize our current state of understanding of the radio emission mechanism and evolution of novae, and focus on how radio observations can test nova models. In Section 2 we describe the standard model for radio light curves (thermal bremsstrahlung from an expanding spherical shell). In Section 3 we discuss estimates of ejecta mass from radio observations, and how models may be refined to produce more accurate ejecta masses. In Section 4, we show some recent evidence that the ejection of material from novae is multi-phase and complex, and illustrate how radio observations can shed light on long-standing observational puzzles at other wavelengths while testing nova theory. In Section 5, we discuss some of the observational effects of a dense circumbinary environment around novae. Finally, Section 6 contains a few concluding remarks.

2. Radio emission from novae

The radio emission from novae is typically much longer lasting than the optical emission, evolving on timescales of years rather than months. Radio observations at a range of epochs yield information on different characteristics of the nova outburst, from the distance to the system at very early times, to the mass of the ejecta as the light curve evolves. Therefore, an observing strategy that monitors novae at both early and late times is crucial to gain a full understanding of their properties.

2.1 "Standard model" of expanding thermal ejecta

Radio emission from novae was first detected by Hjellming & Wade (1970) for HR Del and FH Ser. Both sources were observed to have steep positive spectral indices ($\alpha > 0$, $f_\nu \propto \nu^\alpha$) during the early-time radio light curve, when radio luminosity is increasing with time. This signal was interpreted as optically-thick thermal emission, and showed a brightness temperature comparable to the typical kinetic temperature of electrons in photo-ionized plasma ($T_b \approx 10^4$ K). At late times, when the light curves declined, the spectral index was almost flat ($\alpha \approx -0.1$). Later, these properties were found to be general characteristics of most novae with detectable radio emission.

Thermal bremsstrahlung from the warm ejecta is believed to be the primary mechanism of radio emission from classical novae. There are exceptions like GK Per or RS Oph with significant synchrotron emission in the radio (Seaquist et al. 1989; Anupama & Kantharia 2005; Rupen, Mioduszewski & Sokoloski 2008; Sokoloski, Rupen & Mioduszewski 2008); these are thought to be explosions expanding into unusually dense environs. Overall, non-thermal radio emission from classical novae appears to be rare (Bode, Seaquist & Evans 1987).

At the zeroth order, the thermal bremsstrahlung emission is simple to model, and, with some reasonable assumptions and/or complementary observations, it can be used to derive physical parameters like ejected mass. Such a simple model of thermal emission from an expanding shell of plasma has been used to explain radio light curves from ∼10 novae in the past (e.g. Seaquist & Palimaka 1977; Hjellming et al. 1979; Seaquist et al. 1980; Kwok 1983).

The recent review of radio emission from novae by Seaquist & Bode (2008) comprehensively treats the theory of thermal bremsstrahlung emission from nova shells, and predicted radio light curves. In brief, the model assumes a spherically symmetric isothermal shell of ionized gas with a power law density gradient (radial profile of the number density $n(r) \sim r^p$ where $p = 2 - 3$ is found to be a good fit to most of the observations). The time evolution of the system is introduced through a kinematic model of the expansion of the shell. Different physical models lead to differences in the density profile at relatively small radii, therefore affecting the predicted radio light curves at late times.

For the simplest of these models, known as the "Hubble flow" model, the ejection is instantaneous, the outflow speed increases linearly with radius, and the same amount of mass is expelled at all velocities, implying $p = 2$ (Seaquist & Palimaka 1977; Hjellming et al. 1979; Seaquist et al. 1980; Hjellming 1996). The shell is expelled with a range of velocities (e.g., $\upsilon_{\rm min}/\upsilon_{\rm max} = 0.05$ in Fig. 1), so the shell has a hard inner edge.

In contrast, the "variable wind" model assumes continuous mass loss over an extended time period, significantly longer than the timescale of the radio light curve (Kwok 1983; Hjellming 1990). At all times, mass continues to refill the density profile at small radius, so there is no evacuated cavity at the center of the ejected shell (unlike in the Hubble flow model). It is important to note that, at least for some novae, there is observational evidence of prolonged periods of ejection (e.g. Gallagher & Starrfield 1978). Again, for simplicity $p = 2$ is often assumed in the variable wind model, implying a constant $\dot{M}_w/\upsilon_w$ over time ($p = 2$ is not required by theory of nova winds, but it can be easily solved analytically, while $p = 3$ requires numerical integration; see Seaquist et al. 1980 for a comparison of light curves with $p = 2$ and $p = 3$).

An intuitive tweak to the variable wind model is a wind that varies, and then ceases. In this case, the nova ejecta will detach from the WD and leave a cavity at small radius. This "unified" model essentially combines the variable wind model (at early times) and the Hubble flow model (at late times) to explain the radio light curve of V1974 Cyg, a nova with one of the highest quality radio light curves ever obtained (Hjellming 1996).

For a given kinetic temperature of the plasma, outflow velocity, velocity gradient, total ejected mass, and distance, the Hubble flow model predicts the temporal and spectral behaviour of the radio light curve. It predicts a t^2 rise and a steep spectral index ($\alpha = 2$) for the initial optically thick phase, and a t^{-3} decay with a flat spectral index ($\alpha = -0.1$) for the late time optically thin phase. At intermediate times, when the emission is transitioning from optically thick to optically thin and the radio photosphere is receding through the ejecta, the model predicts $t^{-4/3}$ decline with $\alpha = 0.6$. Historically, this model has been successful in explaining the radio evolution for a number of sources over a range of frequencies and timescales. The observed $\sim t^{-3}$ decay at late times indicates the importance of an inner boundary to the thermal shell; the variable wind model can not reproduce the radio light curve at all time scales. However, a prolonged wind model best explains the very early time optical emission from novae, interpreted as being produced before the ejecta detach from the star — hence, the need for the unified model of Hjellming (1996). Also, please note that all of these scenarios are simplified models, and, in the words of Seaquist & Bode (2008), they are not *"firmly rooted in a detailed understanding of the mass-loss mechanism, but they do constitute at least an initial framework for interpreting the radio data, and for obtaining insight into this mechanism"*.

Fig. 1 shows an example of the best fit Hubble flow model for the multi-frequency radio light curve of V1500 Cyg. The data used here are from Hjellming et al. (1979) and Seaquist et al.

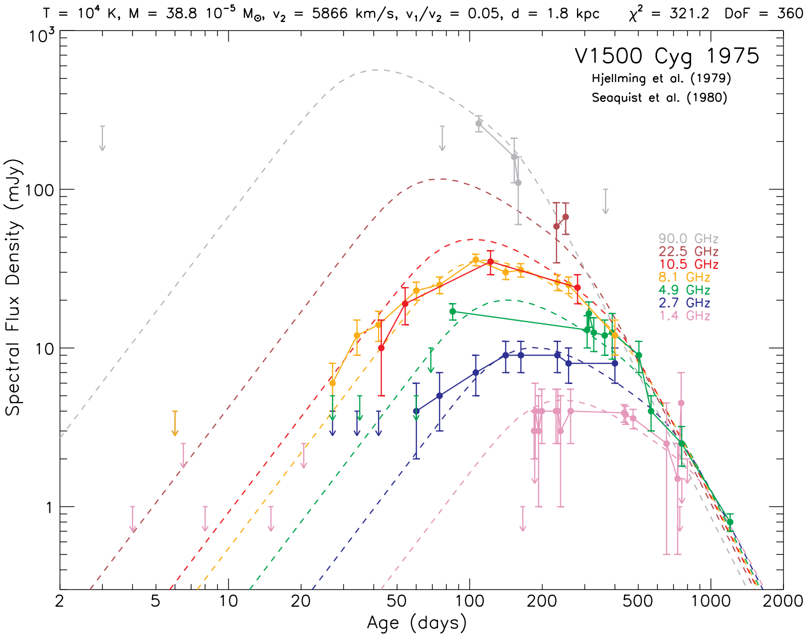

Figure 1. The multi-frequency radio light curve of V1500 Cyg (from Hjellming et al. 1979 and Seaquist et al. 1980), fit by the simple Hubble flow model (dashed lines). The model light curves for 1.4 - 90 GHz matches with the observed values within measurement uncertainties and give reasonable values for the physical parameters like ejecta mass and velocity.

(1980). The model provides reasonable values for physical parameters like ejecta mass ($M_{ej} = 4\times10^{-4}\ M_\odot$) and velocity ($v_{max}$ = 6000 km s^{-1}) for this nova, and provides a good representation of the observed light curves over 1.4 - 90 GHz. However, please note that the measurement uncertainties for the flux densities are quite large here, and hence it would be difficult to notice deviations from the standard model.

2.2 Role of the Karl G. Jansky Very Large Array and of the “E-Nova Project”

Though these models of expanding thermal ejecta were able to fit the multi-frequency radio light curves of a number of novae (e.g., HR Del, FH Ser, V1500 Cyg; Hjellming et al. 1979), there were clear indications of deviations from the simple model in many cases (e.g. Taylor et al. 1987; Hjellming 1996; Lloyd, O’Brien & Bode 1996). Recent work (Johnson et al., in preparation), based on careful review and some reanalysis of the “historical” radio data, shows that such deviations are in fact generic features in the radio light curves of novae. Such deviations may require one or more modifications to the simple model, such as (i) geometrical complexity, e.g., non-spherical ejecta and clumpy small scale structure; (ii) spatial and/or temporal variation of plasma temperature; (iii) multiple episodes of mass ejection; and (iv) interaction with surrounding material giving rise to additional thermal and/or non-thermal components.

The Karl G. Jansky Very Large Array (VLA) is now playing a crucial role in this context. The upgraded new receivers, backend, and correlator provide dramatic improvements in frequency coverage, instantaneous bandwidth, and sensitivity (for a summary of the upgrade, see Perley et al. 2011). The improved sensitivity implies that we are now able to detect the weak radio emission expected within a few days of the optical outburst, so we are observing novae earlier than ever before. We can carry out measurements over a wide range of frequencies (1 – 40 GHz) typically in 1.5 – 2.5 hours of observing time, and constrain the spectral index of radio emission accurately. This spectacular new facility is enabling much more detailed radio measurements of Galactic novae than ever before, and the effort to obtain these exquisite new data is spear-headed by our E-Nova team.

Over the last 2 years, our team has obtained VLA observations of 10 novae within one month of discovery, sometimes as early as 3 days after the onset of the outburst. Many of these observations have resulted in non-detections (Chomiuk et al. 2011a; Nelson et al. 2012b,d), but several novae have been detected early (e.g., Krauss et al. 2010; Chomiuk et al. 2010; Krauss et al. 2011a,b,c; Chomiuk et al. 2012a). Our monitoring program has led us to carry out long term (more than one year) monitoring campaigns on three novae: V407 Cyg, V1723 Aql, and T Pyx, and we are presently beginning monitoring of several younger targets. Essentially, we plan to target new Galactic novae visible to the VLA which are optically bright ($V < 8$ mag, a selection criterion matched by the *Swift* nova group, promising complementary X-ray and UV/optical observations) and/or which show unusual interesting behaviour at other wavelengths, capturing the attention of the broader nova community. After several epochs of VLA observations, we evaluate the strength of radio detection and decide if further follow-up observations are warranted.

In addition to acquiring radio light curves, multi-wavelength partnerships are a critical component of the "E-Nova Project". Our goal is to obtain spatially-resolved radio images (with eMERLIN, VLBA, EVN, and VLA extended configuration), millimetre observations (with SMA, CARMA, and ALMA), X-ray photometry and spectroscopy (with *XMM, Suzaku, Swift*), and high-resolution optical spectroscopy (with FLWO 1.5m, SOAR, and Magellan) for our targets. We also invest significant effort in modeling these observations, to thereby extend and constrain the current models of novae by confronting them with the widest possible range of consistent, high-quality, multi-wavelength data. For some of the details of our VLA observations and results, see Krauss et al. (2011e) and Chomiuk et al. (2012b). Also, see Kantharia (2012, this volume) for a status report and interesting results from lower frequency radio observations of novae using the GMRT.

3. Nova ejecta masses from radio light curves

One of the most exciting prospects for radio observations of novae is the accurate measurement of ejected masses. As we have seen in the previous section, the radio emission from most no-

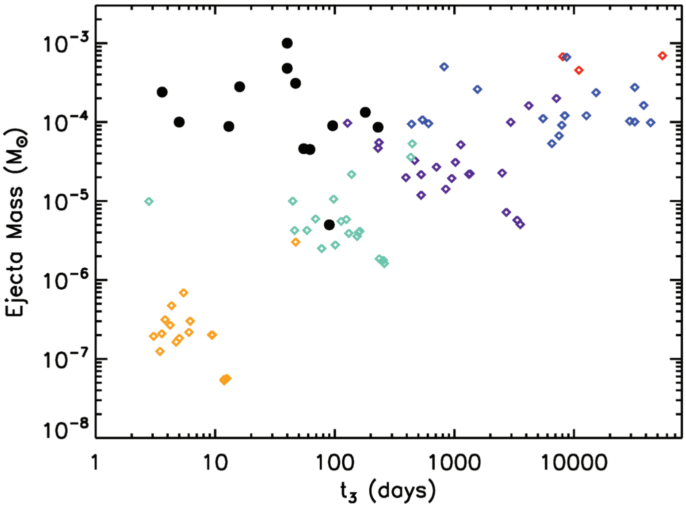

Figure 2. Nova ejecta mass plotted against the time for the optical light curve to decline by three magnitudes (t_3). Theoretical predictions from Yaron et al. (2005) are shown as open diamonds, and color-coded by the mass of the WD that hosts the explosion (red = 0.4 $M_\odot$, blue = 0.65 $M_\odot$, purple = 1.0 $M_\odot$, cyan = 1.25 $M_\odot$, orange = 1.4 $M_\odot$). Observational estimates from radio data are plotted as filled black circles, as compiled by Seaquist & Bode (2008) and Johnson et al. (in preparation).

vae arises predominantly from the thermal ejecta, and as the radio photosphere gradually recedes through the ejecta it samples the entire mass profile. The mass of ejecta is a fundamental prediction of nova models, and thereby provides a direct test of nova theory.

3.1 Testing nova models with observed ejecta masses

In general, the WD properties, like the WD mass, internal temperature, and accretion rate from the companion star, should dictate the fundamentals of the novae explosions, like recurrence time, ejecta mass, and explosion energetics. Theory predicts simple relationships between the WD properties and explosion characteristics (Yaron et al. 2005), but these predicted relationships have been difficult to test observationally. The internal WD temperature is practically impossible to measure, as it is buried deep under the complexities of the accreting WD's surface. In classical novae, the host binary systems are usually not known before nova outburst, and therefore the only hope of constraining WD mass and accretion rate is to study the binary after it returns to quiescence. However, many nova-host binaries are intrinsically very faint at quiescence, and the accretion rate immediately post-nova may not be representative of the average accretion rate (e.g., Shara et al. 1986). In the realm of fundamental explosion properties, we have seen that radio data can provide measurements of the ejecta mass. The luminosity and energetics of the nova explosion should also be measurable, with a suite of multi-wavelength data. Therefore, our best hope for testing theory in a significant sample of novae is to cross-compare different properties of nova explosions, to see if they correlate as predicted and populate the expected parameter space.

It has been pointed out for some time that there is a discrepancy between observed and predicted ejecta masses in novae, where the observed masses are roughly an order of magnitude greater than predicted (Starrfield et al. 1998; Gehrz 2002). This discrepancy is illustrated in Fig. 2, which shows that practically all observed novae have ejecta masses in the fairly narrow range of few $\times 10^{-5}$ to few $\times 10^{-4}$ $M_\odot$, approximately the maximum ejecta mass predicted for *any* parameters in the Yaron et al. (2005) models. In Fig. 2, we plot ejecta mass against optical decline time, and expect these two parameters to be correlated (as in the Yaron et al. models), because the optical photosphere should recede more quickly through less massive ejecta. We do not see any such correlation for the observed novae. The discrepancy between theory and observation is largely due to the fact that the observed novae have relatively fast optical decline times ($t_3 \lesssim 100$ days), which should translate into relatively small ejecta masses ($10^{-7} - 10^{-5}$ $M_\odot$). Few slow or very slow novae have been studied in the radio, to test if the discrepancy persists for long t_3.

Potential physical causes of the discrepancy are poorly understood, although mixing processes are a candidate culprit. Starrfield et al. (1998) suggest that masses of accreted material on the WD could theoretically grow larger if heavy elements (i.e., C/O or O/Ne) are not mixed into the H layer. A lack of mixing would minimize the opacity in the accreted layer, maximize cooling, and maximize the duration of accretion before a thermonuclear runaway ensues. Such a lack of heavy-element mixing might be accomplished if there exists a He-rich buffer layer between the newly-accreted H-rich surface layer on the WD and the heavier-element-dominated WD itself. Of course, this possible explanation is quite speculative, and there are in fact contrasting results from recent numerical simulations (e.g., Casanova et al. 2011; Glasner, Livne & Truran 2011), Clearly, significantly more work — on both observational and theoretical sides — is required to resolve the ejecta mass discrepancy.

3.2 Clumpy nova ejecta can masquerade as massive nova ejecta

On the observational side, several complexities currently limit the accuracy of ejecta mass determinations, with the most significant being clumping in the ejecta. Since the thermal radio emission is directly proportional to the square of the electron density, any clumping will increase the radio flux density and the derived ejecta mass. Volume filling factors of $f = 10^{-1} - 10^{-5}$ are estimated in nova ejecta (e.g., Saizar & Ferland 1994; Mason et al. 2005; Ederoclite et al. 2006; Shara et al. 2012), which can boost the radio luminosity by corresponding factors of 5 – 2000 above what would be emitted for unity filling factor (Abbott, Bieging & Churchwell 1981; Heywood 2004; assuming that all of the emitting material is in the high-density clumps). Current radio models of clumping in novae are relatively simple, assuming a constant filling factor and temperature throughout the ejecta. These simple models scale the radio light curve to be brighter, but do not change the time evolution of the radio light curve.

Clumping was invoked as an explanation of the observed high ejecta mass for V723 Cas by

Heywood et al. (2005). The best fit Hubble flow model to explain the radio flux densities from the MERLIN observations for this source gave an ejecta mass of $1.13 \times 10^{-4} M_{\odot}$, significantly higher than theoretical predictions. Based on this discrepancy, they argued that the ejecta is likely to be clumpy, and hence the actual ejecta mass is lower. This argument was also supported by the irregularities visible on the resolved image of the shell (though much of these were later attributed to instrumental effect due to limited *uv* coverage of the MERLIN observations; Heywood & O'Brien 2007). We are considering clumping in our interpretation of the recently-obtained VLA light curve for the recurrent nova T Pyx (Nelson et al., in preparation). The first nova outburst from T Pyx was detected in 1890, and additional events were observed in 1902, 1920, 1944, 1967, and most recently 2011. Clumping is expected to be important, because T Pyx is surrounded by an Hα+[N II] nebula which is interpreted as the ejecta from previous nova outbursts, and which clearly displays a clumpy morphology (Shara et al. 1997). Our analysis indicates that including clumping in the model may be crucial to explain the radio light curve of T Pyx (Nelson et al., 2012d).

Although some of the discrepancy between predicted and observed ejecta masses could be due to clumping and temperature variations, in actuality a wide range of techniques using diverse wavebands find similar ejecta masses, and they are consistently higher than predicted (e.g., Starrfield et al. 1998; Schwarz 2002; Gehrz 2002). In addition, hints from optical spectroscopy imply the existence of significant reservoirs of gas which will not emit at radio wavelengths, either because they are neutral or very hot (Williams 1994; Ferland 1998). Therefore, most published estimates of ejecta mass are likely lower limits and the discrepancy may be worse than it appears in Fig. 2.

3.3 Ejecta masses in recurrent novae

Recurrent novae (binary systems that have been recorded to host nova outbursts more than once in human history) provide a wealth of information, as compared with classical novae. In recurrent novae, we know the recurrence time between outbursts, and are aware of the binary system over a long time baseline so that significant effort can be invested in measuring the WD mass and accretion rate during quiescence (e.g., T Pyx; Patterson et al. 1998; Selvelli et al. 2008; Uthas, Knigge & Steeghs 2010). Therefore, recurrent novae can provide some of the most stringent and thorough tests of nova theory, allowing us to compare explosion mass and energetics against other fundamental properties of the binary system.

One of the most important predictions of nova models has been that most novae lead to a net loss in mass from accreting WDs, implying severe difficulties in growing WDs to the Chandrasekhar mass so that they explode as SNe Ia. Only less energetic novae outburst, which take place on massive WDs with high accretion rates, should eject less mass than they had accreted since the last nova, allowing them to slowly grow (Yaron et al. 2005; but also see Starrfield et al. 2012 who recently find that WDs grow in mass for a range of outburst parameters). This is also the same class of novae that have relatively short quiescent intervals between outbursts, and will likely be recognized as recurrent novae. Recurrent novae are one of the only tests of whether —

and in what circumstances — accreting WDs can be SN Ia progenitors, by measuring which is larger: the mass ejected in the nova or the accretion rate times the recurrence time. However, the models of Yaron et al. (2005) find that the difference between the accreted and ejected mass is seldom greater than a factor of $\sim$2. Therefore to truly constrain if a WD is growing or shrinking in mass, we need accurate and precise measurements of both the accretion rate and the ejecta mass. Radio observations are key in determining the latter, but unfortunately our interpretation of these data does not yet yield ejecta masses which are sufficiently accurate. Clearly, future work is needed. In this context, with our ongoing analysis of the radio light curve of T Pyx, in near future we will be able to compare the mass of the ejecta in that system to the mass accreted in quiescence (Nelson et al., 2012d).

3.4 Future Prospects for understanding the mass discrepancy

Radio recombination lines (RRLs) of hydrogen have not yet been detected in novae, but they have the potential to shed light on clumping in ejecta, and thereby nova ejecta masses. With measurements of RRLs at a range of frequencies, we could extract the filling factor as a function of radius, along with constraints on density and temperature (e.g., Roelfsema et al. 1991; Anantharamaiah et al. 2000). For a significant RRL detection at a few $\times$10 GHz with the upgraded VLA, we estimate that a nova should have a flux density $\gtrsim$10 mJy and be at least partially optically thin; such flux densities are regularly reached by Galactic novae, so the future looks bright for studies of RRLs in novae.

No matter how accurate our modeling of radio light curves becomes, we must also pursue a multi-wavelength strategy that prioritizes optical spectroscopy, and ideally UV and infrared spectroscopy. Combined studies which take advantage of synoptic spectroscopy, multi-frequency radio light curves, and detailed modeling of multi-wavelength data with CLOUDY hold the most promise for accurate estimates of ejecta mass.

In addition, to fairly characterize the offset between observed and theoretical ejecta masses, and ensure that the suggested discrepancy is not dominated by outliers, we need to constrain the *distribution* of observed nova ejecta masses and compare them with the predicted *distribution*. We require mass estimates — or at least limits on the mass — for a sample of novae representative of the Milky Way population. Currently, targets for multi-wavelength follow-up are rarely chosen because they are representative, but instead because they are particularly interesting in some waveband or because they are optically bright. This has likely biased our samples of novae in difficult-to-quantify fashion. In addition, radio non-detections of novae have rarely been published, leading to a bias where only the most massive novae are permitted onto Fig. 2. At present, it is difficult to assess if the paucity of novae with observed ejecta masses $< 10^{-5}$ M$_\odot$ is due to this bias, or if low-mass ejecting novae really do exist in smaller numbers than predicted by theory. To make progress on this question and test if observed novae are consistent with theoretical predictions, we require an observing philosophy that prioritizes completeness, understanding of selection effects, and inclusion of censored data. Future radio transient surveys of the Galactic

Bulge, like ThunderKAT with MeerKAT, should make significant progress on our understanding of the discrepancy between observed and predicted ejecta mass.

4. Complex multi-phase ejections traced by radio light curves

All models of the radio emission from novae presented in this review assume a smooth homologous flow with velocity gradient for the ejecta that has the fastest material on the outside, and slowest material in the interior of the shell. However, complementary observations at other wavelengths illustrate the complexity of mass ejection in novae. In particular, hard X-ray emission is detected in a growing number of novae at early times, and has been interpreted as evidence of fast material ejected at late times sweeping up, and shock heating earlier, slower ejecta to X-ray emitting temperatures - the exact *opposite* of the velocity gradient in the radio models (O'Brien, Lloyd & Bode 1994; Mukai & Ishida 2001; Mukai, Orio & Della Valle 2008). From optical spectroscopy also, it was suggested that the velocity of the nova wind may increase with time, so that material expelled at later times catches up with earlier-expelled material and produces shocks (Friedjung 1987; Warner 2008). A two phase wind mass loss model was proposed by Kwok (1983) to explain the optical and radio data for a few novae. In addition, many features of nova optical light curves remain poorly understood. While some light curves simply decline as expected for a receding photosphere in expanding ejecta, others show plateaus that can last from days to months (Kato & Hachisu 2011), or multiple secondary maxima (e.g., Munari et al. 2008; Hounsell et al. 2010) — consistent with "stalled-out" or growing optical photospheres. Radio observations can shed light on the mechanisms and history of mass ejection in novae, and on these puzzling multi-wavelength phenomena, because they are an excellent probe of the density profile of the ejecta.

4.1 Early time bumps in radio light curves

The first clear example of an early-time anomalous maximum in a nova radio light was the 1984 explosion of QU Vul (Taylor et al. 1987; Fig. 3). Regrettably, the first epoch of radio observation was not until 206 days after discovery, but it revealed a very high flux density at 15 GHz (63 mJy) and a very steep spectral index of α = 2.4. Over the next ~50 days, the 15/22 GHz light curves declined while 1.5/4.9 GHz light curves gently rose, leading to a flattening of the spectral index. Late time evolution of QU Vul was roughly consistent with the standard model of expanding thermal ejecta, showing a secondary maximum at high frequencies and continued rise at low frequencies. Taylor et al. (1987) show that the early time bump could be the signature of a multiphase ejection, wherein a shell is expelled at early times, followed by a faster wind which shocks this shell. In their model, the velocity differential between the shell and wind is of order ~200 km s^{-1}, and the shocked material emits optically thin thermal emission at radio wavelengths. However, this shock is embedded in the ionized ejecta, which provides an absorbing screen at radio wavelengths and leads to the observed α = 2.4.

More recently, our extensive monitoring of the classical nova V1723 Aql also shows unusual

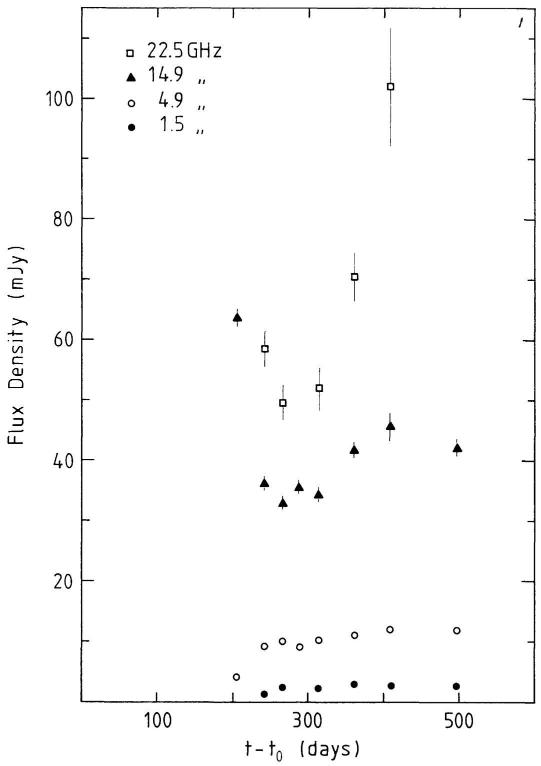

Figure 3. VLA radio light curves of QU Vul spanning 1.5 - 22.5 GHz (Taylor et al. 1987). In the first few epochs, the higher frequencies are anomalously bright, but they subsequently fade to participate in the evolution expected from the standard model of expanding thermal ejecta.

behaviour and significant departure from the Hubble flow model predictions (Krauss et al. 2011e). The VLA multi-frequency light curve for this source is shown in Fig. 4. There is a bump with very fast ($\sim t^{3.3}$) rise. Unlike in QU Vul, as the flux density rises to this early time bump, the spectral index *flattens* from $\alpha = 1.1$ to $\alpha = 0.4$ around the ~ day 50 maximum. Subsequently, the flux densities at lower frequencies decrease significantly but the light curves at higher frequencies remain relatively constant (resulting in a steepening of the spectral index). Both the temporal and spectral evolution of V1723 Aql are dramatically different from that of the Hubble flow model (shown as dashed lines in Fig. 4). The difference arises from the maximum at early times, but our ongoing monitoring indicates that the late time light curve is probably settling into a Hubble-flow-like behaviour. There is no indication of a dense environment for this source, and neither the low frequency flux density limits nor the spectral indices are consistent with a significant non-thermal component. A model similar to that developed by Taylor et al. (1987) might apply in the case of V1723 Aql, if the absorbing screen is less dense and does not play a significant role in steepening the spectral index. The Swift XRT detection of hard X-ray emission from V1723 Aql around the

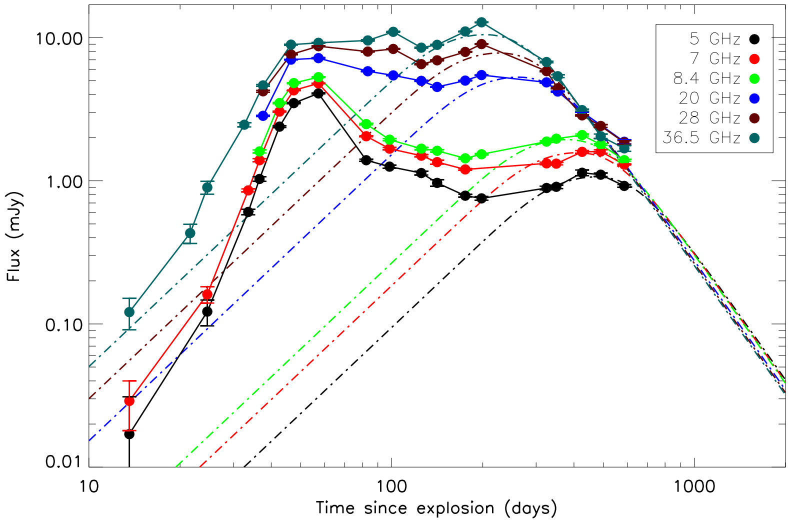

Figure 4. VLA radio light curves of V1723 Aql spanning 5 - 40 GHz. The light curves have a rapid initial rise ($f_\nu \propto t^{3.3}$) to an anomalous peak around day 50 with a nearly flat spectrum. The best fit Hubble flow model shows that late-time data probably adhere to the standard model of expanding thermal ejecta.

~ day 50 bump indicates the presence of shock. Further follow up observations, as well as more detailed analysis and modeling for this source is in progress (Weston et al., in preparation).

Although we are currently limited by a sample size of two, the comparison of V1723 Aql and QU Vul demonstrates diversity of early time radio bumps, both in rise/decline times and radio spectral indices. This diversity underscores the potential richness of radio light curves at early times, and it remains to be seen if the same underlying physical process can explain the full range of observations.

4.2 Delayed rises of radio light curves

Because the radio light curve traces the mass and extent of the ionized nova ejecta, it is an elegant tracer of *when* the mass is actually expelled. While most historical light curves of novae in the radio are consistent with the ejection of mass around the time of optical discovery, our recent VLA data on T Pyx is an intriguing counter-example.

Our multi-frequency light curves of the 2011 outburst of T Pyx started rising surprisingly late, about 80 days after the optical outburst (Chomiuk et al. 2011b, Krauss et al. 2011d, Nelson et al., 2012d). The rise is wholly inconsistent with expulsion at the time of optical discovery, and instead implies that the gaseous envelope was in rough hydrostatic equilibrium for a couple months, until it suddenly started to expand. The time of radio rise also coincides with the time of a sharp decline in the optical light curve, which had been experiencing plateau-like behaviour around maximum prior to ∼ day 80. This is as expected if the optical photosphere begins to recede when the ejecta begin bulk expansion. Such a delayed discrete episode of mass loss is unprecedented in radio observations of novae, although previous observations may have had limited sensitivity to small delays in ejection because of the poor early-time coverage typical in radio light curves. Optical light curves of novae do regularly show plateaus of various durations, but this behaviour was poorly understood. For the first time, in T Pyx, our radio observations may clearly link plateaus with delayed ejection. In the future, we plan to test if pre-maximum halts (as seen in the optical, Hounsell et al. 2010) and other plateaus always coincide with delayed mass ejection, as traced by radio light curves.

4.3 Testing models of mass ejection in novae

Features such as multi-phase and delayed ejections clearly show that richly varied physical processes are instrumental in ejecting material from the surface of the WD. The next step is to test, in detail, if this clearly observed complexity in mass ejection is consistent with theoretical predictions.

While complex multi-phase ejection histories are predicted by models that combine hydrodynamics and networks of nuclear reaction rates to simulate nova explosions (Prialnik 1986), previous work has focused on the simplest modeled quantities (e.g., total ejecta mass, maximum velocity). The extensive grid of models used to predict these simple quantities (e.g., Yaron et al. 2005) also produces detailed mass-loss histories for simulated novae, but these results remain unpublished (M. Shara 2012, private communication). The E-Nova Project plans to carry out a detailed comparison between model predictions of mass loss histories from novae and modern multi-wavelength data, with radio observations leading the charge and tracing the bulk of the ejected mass.

Radio observations can produce some of the highest resolution images in all of astronomy, and high-resolution arrays like eMERLIN, VLBA, and VLA in A configuration are all undergoing dramatic upgrades. In the future, our observational capabilities promise to keep pace with advances in theory brought on by multi-dimensional simulations of novae, which are only in their infancy but already revealing new insights into long-standing problems in our understanding of nova explosions (Casanova et al. 2011).

5. The effect of environment on radio light curves

The environments surrounding novae can also impact the evolution of radio emission from these explosions and affect our ability to derive fundamental explosion parameters from nova light curves. At the same time, radio emission from “embedded” novae (surrounded by dense environments) can provide rich insights into the nature of circumstellar material in binary systems. If, as proposed by Williams & Mason (2010), significant reservoirs of circumbinary material are commonly present around novae, interaction between the ejecta and this material should modify the radio light curve considerably.

When nova ejecta interact with a dense environment, a strong shock should be formed, which in turn may give rise to a synchrotron emission component. In a few cases, like RS Oph (Hjellming et al. 1986; Taylor et al. 1989; O'Brien et al. 2006; Rupen, Mioduszewski & Sokoloski 2008; Sokoloski, Rupen & Mioduszewski 2008) and GK Per (Seaquist et al. 1989; Anupama & Kantharia 2005), synchrotron emission is found to be the significant, or sometimes even the dominant, emission component. The Fermi detection of the recent nova in V407 Cyg revealed that shock interaction with a dense environment can also lead to GeV gamma ray emission in novae (Abdo et al. 2010). Recently, the Fermi collaboration reported another possible gamma ray transient associated with a nova (Cheung et al. 2012). We have obtained early time radio data for this source, Nova Sco 2012, and our preliminary analysis reveals a spectral slope that is compatible with non-thermal emission, as expected if a strong shock interaction is taking place (Chomiuk et al. 2012a).

Interactions between nova ejecta and circumbinary material may also give rise to thermal radiation produced by the ionization of circumbinary material by the nova outburst. From our VLA observations of the 2010 nova in the symbiotic binary V407 Cyg, we see clear and strong effects of the dense wind from the Mira giant companion in the radio light curve. More than two years of VLA monitoring shows that the radio evolution of V407 Cyg can not be reconciled with the standard model of expanding thermal ejecta. The bright radio flux densities would require a massive ejection ($10^{-5} - 10^{-4} M_\odot$), directly in conflict with other observations suggesting a low ejecta mass ($10^{-7} - 10^{-6} M_\odot$; Munari et al. 2011; Schwarz et al. 2011; Nelson et al. 2012a). Even with massive ejecta, the observed spectral indices are inconsistent with thermal nova ejecta. For this source, we developed an alternative detailed model of thermal radio emission from the surrounding dense Mira wind which was ionized by the nova outburst. Our data suggest that this mechanism can produce the observed radio luminosity consistently. The rising part of the radio light curve is due to the increasing ionization of the wind, whereas the nova shock from within causes the declining part. There is no evidence of additional emission components, from either thermal nova ejecta or synchrotron shocks; these components were likely present but hidden behind the absorbing screen of the ionized Mira wind. Our VLA observations and detailed modeling of the radio emission are presented in Chomiuk et al. (2012b).

While RS Oph, GK Per, and V407 Cyg are clearly extreme examples of dense environments around novae, it is likely that all novae lie on a continuum of environmental densities. Other more "classical" novae may show subtle yet detectable effects of circumbinary material in radio light curves; the more extreme embedded novae are useful for demonstrating and calibrating the observational effects of such interaction.

6. Concluding remarks

With radio and millimeter astronomy on the cusp of enjoying many new exciting facilities, radio studies of novae are undergoing a renaissance. With the upgraded VLA, we have started detecting many unforeseen complexities in radio light curves, which demand refinement of models of radio emission from novae and provide opportunities for testing models of the nova explosions themselves. From the historical framework developed by R. Hjellming, E. Seaquist, A. R. Taylor, and others, it is clear that radio observations provide unique insights into nova explosions, because they trace thermal free-free emission, and by extension, the bulk of the ejected mass. Radio thermal optical depth evolves on very different timescales, as compared with optical observations. In addition, radio observations are not subject to the many complex opacity and line effects that optical observations both benefit and suffer from. This means that not only can radio observations be much more convenient to obtain and interpret, but they can also probe how the ejecta profile and dynamic mass loss evolve with time. Continuing our systematic radio monitoring with complementary multi-wavelength campaigns, and improving the models as demanded by the data, we are confident that radio observations of novae will illuminate the many multi-wavelength complexities observed in novae and test models of nova explosions.

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