Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS 456, L49–L53 (2016) doi:10.1093/mnrasl/slv154

Insights into the evolution of symbiotic recurrent novae from radio synchrotron emission: V745 Scorpii and RS Ophiuchi

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Accepted 2015 October 7. Received 2015 August 19; in original form 2015 May 23

ABSTRACT

We present observations at 610 and 235 MHz using the Giant Metrewave Radio Telescope (GMRT) of the recurrent nova V745 Scorpii which recorded its last outburst on 2014 February 6. This is the second symbiotic recurrent nova whose light curve at low frequencies has been followed in detail, the first being RS Ophiuchi in 2006. We fitted the 610 MHz light curve by a model of synchrotron emission from an expanding shell being modified by radiative transfer effects due to local absorbing gas consisting of a uniformly distributed and a clumpy component. Using our model parameters, we find that the emission at 235 MHz peaked around day 35 which is consistent with our GMRT observations. The two main results of our study are (1) The radio emission at a given frequency is visible sooner after the outburst in successive outbursts of both V745 Scorpii and RS Ophiuchi. The earlier detection of radio emission is interpreted to be caused by decreasing foreground densities. (2) The clumpy material, if exists, is close to the white dwarf and can be interpreted as being due to the material from the hot accretion disc. The uniform density gas is widespread and attributed to the winds blown by the white dwarf. We present implications of these results on the evolution of both novae. Such studies along with theoretical understanding have the potential of resolving several outstanding issues such as why all recurrent novae are not detectable in synchrotron radio and whether recurrent novae are progenitor systems of Type 1a supernova.

Key words: binaries: symbiotic – stars: dwarf novae – radio continuum: stars.

1 INTRODUCTION

Recurrent novae are binary systems with the primary being a white dwarf and the secondary a red giant or a main-sequence star. A symbiotic recurrent nova is a system comprising a red giant secondary. The white dwarf accretes matter from the secondary which leads to a runaway thermonuclear explosion on its surface after a critical mass is reached. This results in a spectacular increase in optical light by a few to 15 mag.

The last outburst of the recurrent nova V745 Sco, predicted by Schaefer (2010) to be in year 2013 ± 1, was recorded on 2014 February 6 (Rod Stubbings, AAVSO special notice 380). The previous outbursts in V745 Sco were recorded on 1937 May 10 and 1989 July 30 (Duerbeck 1989). The current outburst has been detected in bands ranging from the γ-rays (Cheung, Jean & Shore 2014) to low-frequency radio waves (Kantharia et al. 2014).

In this paper, we describe the low radio frequency observations of V745 Sco with Giant Metrewave Radio Telescope (GMRT) and combine it with Very Large Array (VLA) archival data from the 1989 outburst to understand the evolution of the system. We also study the results on the symbiotic recurrent nova RS Ophiuchi from its outbursts in 1985 and 2006.

2 OBSERVATIONS, DATA ANALYSIS AND RESULTS

The GMRT (Swarup et al. 1991) observations of V745 Sco were conducted either in the 610 MHz band or in the dual band which allows simultaneous observations in both the 235 and 610 MHz bands between 2014 February 7 and September 7. Bandwidth settings of 32 MHz at 610 MHz and 16 MHz at 235 MHz were used. A

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Table 1. GMRT results on V745 Sco at 610 and 235 MHz. t_0 is 2014 February 6. The flux density of the background source (bcksrc) is estimated from the image whereas the flux density of the phase calibrator J1830−360 is obtained from GETJY.

t–t_0	Date	Flux density at 610 MHz				Flux density at 235 MHz				α_{610}^{235}
		V745Sco	σ	bcksrc	J1830−360	V745Sco	σ	bcksrc	J1830−360	
(d)	2014	(mJy beam^{-1})	(mJy beam^{-1})	(mJy)	(Jy)	(mJy beam^{-1})	(mJy beam^{-1})	(mJy)	(Jy)	
3	Feb 9	<0.55	–	16.26(0.16)	18.1(0.17)	–	–	–	–	
12	Feb 18	1.07	0.14	16.41(0.14)	16.87(0.05)	–	–	–	–	
27	Mar 05	6.9	0.13	17.04(0.13)	18.07(0.11)	–	–	–	–	
28	Mar 06	6.8	0.17	15.3(0.11)	16.63(0.11)	4.3	0.9	30.9(0.9)	29.44(0.3)	0.49
35	Mar 13	5.89	0.18	14.76(0.1)	16.27(0.16)	4.7	1.1	31.2(1.2)	30.1(0.4)	0.24
40	Mar 18	5.11	0.13	15.91(0.13)	17.39(0.22)	<4.5	–	28.7(1.6)	32.5(0.7)	>0.13
47	Mar 25	3.83	0.18	15.64(0.18)	16.95(0.15)	5.4	1.4	30.7(1.4)	31.9(0.7)	−0.37
56	Apr 03	3.38	0.07	18.06(0.19)	17.25(0.42)	<6	–	43.1(0.98)	30.73(2.11)	>−0.6
71	Apr 18	2.52	0.19	18.08(0.19)	19.2(0.4)		–	–	–	
86	May 03	2.06	0.07	17.59(0.07)	18.54(0.08)	–	–	–	–	
101	May 18	1.17	0.21	13.42(0.22)	16.44(0.94)	<4.5		25.1(1.15)	28.44(0.29)	>−1.4
123	June 09	1.11	0.14	16.1(0.12)	17.58(0.07)	–	–	–		
154	July 10	0.99	0.099	17.5(0.11)	18.33(0.09)	–	–	–		
187	Aug 12	0.72	0.1	17.3(0.1)	17.86(0.16)	–	–	–		
217	Sep 07	0.48	0.12	16.6(0.07)	18.17(0.23)	<5.7	–	26.3(1.8)	30.04 (0.45)	

combination of Director's Discretionary Time and regular allocation time in Observing Cycle 26 as part of the project *Galactic Novae with GMRT* (GNovaG) were used for GMRT observations. The observations started with a 10 min run on an amplitude calibrator (3C286 or 3C48) followed by 3 min and 30 min runs on the phase calibrator (J1830−360) and V745 Sco. Most of the observing slots were ∼2 h in duration with ∼1.5 h on the nova and resulted in ∼ 90 µJy rms noise on the final image at 610 MHz.

The data were converted from the native *lta* format into FITS format and imported into AIPS.[1] These data were calibrated and imaged using 25 facets at 610 MHz and 49 facets at 235 MHz. The synthesized beamshapes were elliptical with typical sizes being 10 arcsec × 5 arcsec at 610 MHz and 20 arcsec × 10 arcsec at 235 MHz with a position angle ∼30°.

The results of GMRT observations of V745 Sco are listed in Table 1 and shown in Fig. 1. The first detection was on day 12 (18/2/2014) after the recorded outburst. Due to a position offset in the map, Kantharia et al. (2014) missed reporting the detection on day 12. Observations on 2014 March 6 detected a strong radio source at both 610 and 235 MHz. No correlation between the varying strength of the target source and the calibrators is observed (Table 1).

We analysed the VLA archival data of V745 Sco from 1989 and the results are shown in Table 2 and Fig. 1. The data on RS Ophiuchi are obtained from literature – the 1.4 GHz data from the 1985 outburst is from Hjellming et al. (1986) and the model fit to the 2006 outburst is from Kantharia et al. (2007).

3 INTERPRETING THE OBSERVATIONS AND MODELLING THE LIGHT CURVES

V745 Sco is the second symbiotic recurrent nova which has been studied at GMRT frequencies where the emission is predominantly synchrotron in nature. The peak radio power estimated for a distance of 7.8 ± 1.8 kpc (Schaefer 2010) at 610 and 235 MHz are, respectively, 4.7×10^{13} and 4×10^{13} W Hz^{-1}. For comparison, the peak power from RS Ophiuchi at 610 MHz following its outburst in 2006 (Kantharia et al. 2007) was 1.5×10^{13} W Hz^{-1}.

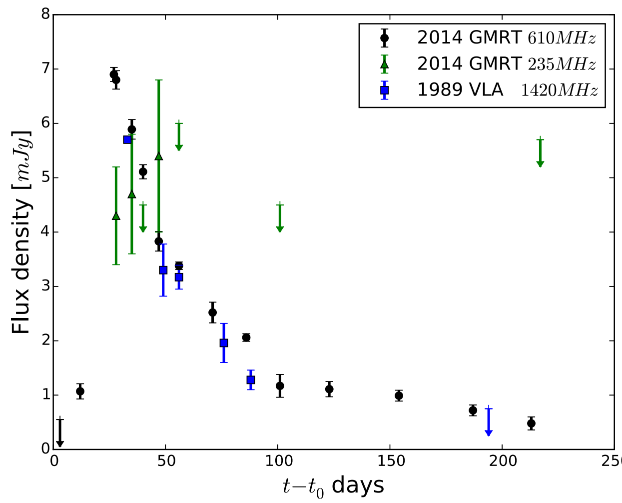

Figure 1. Light curve of V745 Scorpii: 610 and 235 MHz from the 2014 outburst using GMRT and 1.4 GHz from the previous outburst in 1989 using VLA archival data. t_0 is 2014 February 6.

Table 2. Analysis of VLA archival data (AH 383, AH 389) at 1.4 GHz on V745 Sco following the outburst in 1989. t_0 is 1989 July 30.

t–t_0 (d)	date	S (mJy)	Reference
33	1989 Sep 01	5.7	Hjellming (1989)
49	1989 Sep 17	3.3(0.48)	VLA archives
56	1989 Sep 24	3.17(0.22)	VLA archives
76	1989 Oct 07	1.96(0.36)	VLA archives
88	1989 Oct 19	1.28(0.18)	VLA archives
194	1990 Feb 02	<0.75	VLA archives (3σ)

Assuming equipartition of energy between the relativistic particles and magnetic field, expected under minimum energy condition, we estimate a magnetic field of 0.03 G and energies of $\sim 10^{32}$ Joule

[1] AIPS is produced and maintained by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

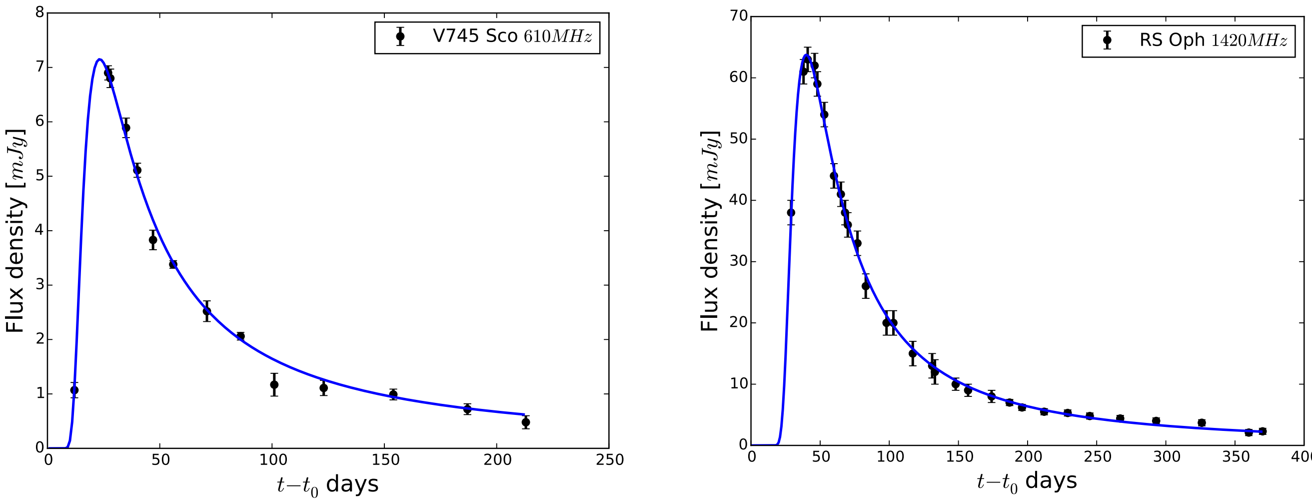

Figure 2. Left: the best model fit (solid line) to the light curve of V745 Sco at 610 MHz from its outburst in 2014. Right: the best model fit (solid line) to the light curve of RS Ophiuchi at 1.4 GHz from its outburst in 1985. Data points are taken from Hjellming et al. (1986).

Table 3. Model outputs. The spectrum is assumed to have a spectral index $\alpha = -0.5$. Emission measure (EM_{peak}) of absorbing gas when the optical depth is one. The electron temperature is assumed as 10^4 K. N is the number of detections, t_{peak}, S_{peak}, $t_{1\,per\,cent}$ refer to the day on which peak emission occurred, peak emission strength and the day on which the emission was 1 per cent of peak emission. β is the temporal decay index, K_2, $\delta_{uniform}$, K_3, δ_{clumpy} are the constants from equation (1).

Nova	Outburst epoch	ν	N	t_{peak} (d)	S_{peak} (mJy)	$t_{1\,per\,cent}$ (d)	β	K_2	$\delta_{uniform}$	K_3	δ_{clumpy}	χ^2_{red}	EM_{peak} (cm^{-6}pc)
V745 Sco	2014	610 MHz	14	23	7.1	9.5	−1.3	65.8	−3	0.8	−4.8	1.2	10^6
	1989	1.4 GHz	5	18	8.7	7	−1.4	–	−2.9	–	−6.3	4	6×10^6
RS Ophiuchi	2006[1]	610 MHz	14	29	52.9	6	−1.24	0.14	−2.29	0.53	−3.14	1.5	10^6
	1985[2]	1.4 GHz	30	40	63.8	20.5	−1.7	53060	−3.9	9.8	−4.6	0.54	6×10^6

Notes. [1]Parameters from the multifrequency light curve fits in Kantharia et al. (2007).
[2]The 1985 light-curve data at 1.4 GHz is taken from Hjellming et al. (1986).

for the 2014 outburst of V745 Sco. An emitting shell of radial extent 1 au was assumed at a distance of 30 au from the white dwarf as inferred from the near-infrared (Banerjee et al. 2014) and X-ray observations (Orio et al. 2015). A magnetic field of strength 0.04 G with energy in relativistic particles being 2.8×10^{31} Joule i.e. about 0.02 per cent of total energy was estimated for the 1985 outburst in RS Ophiuchi (Bode & Kahn 1985). The magnetic field strengths and particle energies match to within an order of magnitude in the two recurrent novae and for two consecutive outbursts.

We use the parametric model that has been presented in equation (1) in Weiler et al. (2002) for explaining supernova light curves. The assumptions in the model are implicitly included and we do not explore any possible differences due to the observed bipolar nature of synchrotron emission from RS Ophiuchi in its 1985 outburst (Taylor et al. 1989) and its 2006 outburst (O'Brien et al. 2006). In the Weiler et al. (2002) model, there is a frequency-dependent delay in the detection of synchrotron emission due to the opacity of the foreground thermal gas. The radio emission rises as opacity decreases with peak emission at unity opacity and then declines as the emitting shell expands. The model includes opacity due to several different components. We only included the local opacities due to the uniform and clumpy parts of the circumbinary material which well explained the light curves from the 2006 outburst in RS Ophiuchi (Kantharia et al. 2007). This model was fitted to the light curves at 610 MHz from the 2014 outburst (Fig. 2) and at 1.4 GHz from the 1989 outburst in V745 Sco and to the 1.4 GHz data from the 1985 outburst in RS Ophiuchi (Fig. 2). The model outputs are listed in Table 3.

3.1 The free–free optical depth variation in V745 Sco

Using the model parameters listed in Table 3, we have plotted the variation in the optical depth with time (see equation 1 and Fig. 3 top). The temporal variation in the optical depth due to uniformly distributed gas, $\tau_{uniform}$ and the clumpy gas, τ_{clumpy} is (Weiler et al. 2002)

$$\tau_{uniform}[\tau_{clumpy}] = K_2[K_3]\left(\frac{\nu}{5\,\mathrm{GHz}}\right)^{-2.1}\left(\frac{t-t_0}{1\,\mathrm{d}}\right)^{\delta_{uniform}[\delta_{clumpy}]} \quad (1)$$

K_2, K_3, δ are determined from the fits to the light curve (see Table 3). The variation in both optical depths at three frequencies 235, 610 and 1.4 GHz is shown in Fig. 3. As seen in the figure, τ_{clumpy} drops to one within five days following the outburst at all bands. $\tau_{uniform}$ shows a slower decline – is one around day 10 at 1.4 GHz, day 18 at 610 MHz and day 35 at 235 MHz which would roughly correspond to the peak emission at those bands. Our observations at 235 MHz are consistent with this model. Thus, the turn-on of the synchrotron emission at the low radio frequencies is determined primarily by the optical depth of the uniform density gas in the 2014 outburst of V745 Sco. Due to the absence of data points leading to the peak of

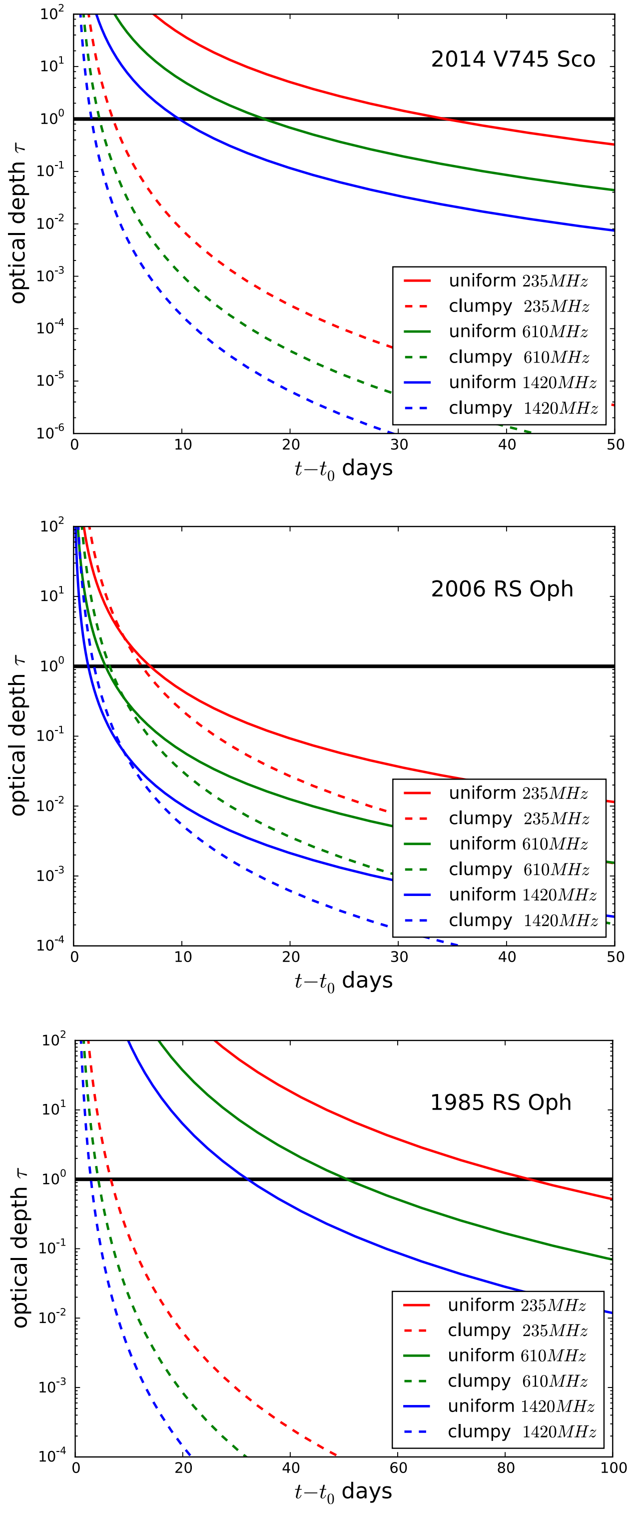

Figure 3. The evolution of the optical depth due to the uniform density and clumpy medium in the nova system for (top) 2014 outburst of V745 Sco, (centre) 2006 outburst of RS Oph using parameters given in Kantharia et al. (2007), (bottom) 1985 outburst of RS Ophiuchi. Clumpy medium shows similar behaviour for the outbursts in 1985 and 2006 whereas the uniform density medium shows evolution. The large optical depths are not physical and are shown only to indicate total absorption. The region of interest is close to where opacity is one as indicated by the black horizontal line.

the 1989 outburst (see Table 3), all the model parameters are not well constrained and do not allow a study of the opacity variation. The temporal flux variation is similar in both epochs. The model fit predicts the peak at 1.4 GHz in 1989 to have been around day 18 as compared to day 10 in 2014. This suggests evolution in the environment of the nova.

3.2 The free–free optical depth variation in RS Ophiuchi

We also did a similar study of opacity variation in RS Ophiuchi using our model fit to the 1.4 GHz data from the 1985 outburst taken from Hjellming et al. (1986) and the Kantharia et al. (2007) fit parameters for the 2006 outburst (Fig. 3). Interestingly, the variation in opacities due to uniform density gas and clumpy gas is comparable following the outburst in 2006 whereas the 1985 fit shows a rapid fall in $\tau_{\rm clumpy}$ as noted for V745 Sco in 2014. The differences in the 1985 and 2006 outbursts of RS Ophiuchi are (1) The turn-on in 2006 at a given frequency occurs at an earlier date following the outburst as compared to the 1985 outburst. (2) The turn-on day in 1985 is primarily determined by the uniform density gas whereas in 2006, it is determined by both the uniform density and clumpy gas. (3) The $\tau_{uniform}$ in 1985 falls to unity around day 32 at 1.4 GHz and day 85 at 235 MHz whereas in 2006, it is unity around day 2 at 1.4 GHz and around day 8 at 235 MHz. We infer the net effect to be reduction in the ambient ionized gas densities in 2006 as compared to 1985. Kantharia et al. (2007) had arrived at a similar result using the 325 MHz data from 2006 when it was detected on day 38 and using the result from 1985 that no emission was detected up to day 66 (Spoelstra et al. 1987) and inferred that the absorbing densities in 2006 were about 30 per cent of those in 1985. The model fitted to the 1985 1.4 GHz data on RS Ophiuchi is consistent with this conclusion and suggests that the emission at 325 MHz would have been visible ∼ day 66 in 1985.

3.3 Comments on evolution of novae from opacity variation

Our main results from the synchrotron light curve fitting for both the novae are: (1) earlier turn-on and peaks observed at a given frequency following an outburst for successive outbursts, (2) clumpy material distributed closer to the system and uniformly distributed gas being more widespread. In Table 3, we have listed the emission measure (EM) of the foreground thermal gas when it would be transparent to the emission at 610 and 1.4 GHz. The earlier peaks with successive outbursts would indicate reducing EM of the absorbing gas.

Theoretical studies indicate that when the accretion rate exceeds some critical limit (few times 10^{-7} $M_\odot$ yr^{-1}; Hachisu & Kato 2001), then the envelope on the white dwarf can expand to the size of a red giant (Nomoto 1982). This can then lead to the formation of a common envelope (e.g. Nomoto, Nariai & Sugimoto 1979) which can trigger a spiral-in of the binary and a double degenerate system (Iben & Tutukov 1984). Hachisu, Kato & Nomoto (1996) found that another outcome of the larger accretion rate would be fast optically thick winds (∼1000 km s^{-1}, ≥ 10^{-6} $M_\odot yr^{-1}$) blown by the white dwarf which they refer to as accretion winds. The accretion winds would stabilize the system and the binary continues to evolve as a single degenerate system (Hachisu et al. 1996). The accretion rates for V745 Sco and RS Ophiuchi were estimated to be 2×10^{-7} $M_\odot$ yr^{-1} (using a recurrence time-scale of 25 yr) and 1.2×10^{-7} $M_\odot$ yr^{-1} (Hachisu & Kato 2001). Combining our results with the theoretical arguments, we infer the following.

(1) The onset of synchrotron radio emission is delayed by the optically thick winds blown by the white dwarf which constitutes the uniform density component. The clumpy component rapidly gets transparent. We suggest this to be due to the material from the accretion disc close to the white dwarf which is blown off in each outburst (Hachisu & Kato 2001).

(2) The earlier turn-on of the radio emission with successive outbursts would then indicate the reduction in emission measure of the accretion winds. This could imply a reduced accretion rate ($<$ few times 10^{-7} $M_{\odot}yr^{-1}$) on the white dwarf. The estimated accretion rate on both the novae is about 10^{-7} $M_{\odot}$ yr^{-1}. If indeed the accretion rate has dropped causing the winds to stop – either the two stars can spiral-in leading to a double degenerate system or if the white dwarf is massive enough, it can explode as a Type 1a supernova. If the latter is not the case, then there are reasons to believe that the single degenerate system might not evolve into a Type 1a supernova.

(3) Alternately since the mass of the white dwarfs in both systems is believed to be close to the Chandrasekhar limit, the critical accretion rate limit is larger at 10^{-6} $M_{\odot}$ yr^{-1} (Nomoto 1982). Since the estimated accretion rates are lower than this larger critical limit, it would cause the winds to stop as the white dwarf grows in mass, leading to a transparent ambience at radio wavelengths. From our results on V745 Sco and RS Oph over two outbursts, it can be surmised that the synchrotron emission at 610 MHz in the next outburst from V745 Sco should be detected before day 9.5 and from RS Oph before day 6. If the accretion rate has reduced, then it would lengthen the period between two outbursts – however if only the accretion winds have stopped, this should have no effect on the outburst frequency.

(4) The electron energy spectrum set up by the shock in two distinct outbursts appear similar for the two systems studied here. Multifrequency radio synchrotron data is required for further study which is feasible in future outbursts in the fast-evolving recurrent nova systems provided time allocation is made faster on major radio telescopes.

4 SUMMARY AND CONCLUSION

In this paper, we have presented our observations, at 610 and 235 MHz using the GMRT, of the recurrent nova system V745 Sco following its outburst in 2014. The parametric model including opacities due to clumpy and uniform media in Weiler et al. (2002) explains the light curves of V745 Sco and RS Ophiuchi. We conclude the following from our study.

(1) The radio synchrotron emission is visible sooner after the outburst, with each outburst. In V745 Sco, the 610 MHz emission peaked $\sim$ day 23 in 2014 and $\sim$ day 18 at 1.4 GHz in the 1989 outburst. Our model fit predicts that the 1.4 GHz emission would have peaked $\sim$ day 10 in 2014. In RS Ophiuchi, the radio synchrotron emission at 1.4 GHz turned on day 20.5 in 1985 whereas the first detection in 2006 was on day 4.7 (Eyres et al. 2009).

(2) The circumbinary material in the recurrent nova with a red giant companion is evolving with time. Clumpy material lies closer to the system compared to the extent of the uniform medium. This material could be due to the accretion disc of the white dwarf which is destroyed with each outburst. The uniform density component is caused by the hot optically thick winds blowing from the white dwarf. The earlier visibility could indicate that the winds are arrested due to the accretion rate falling below some critical rate for a given white dwarf mass. This could lead to multiple evolutionary scenarios which need to be investigated further. Interestingly, Williams (2013) also required a medium with clumpy and uniform components to explain optical and X-ray data. Well-sampled multifrequency data during the rise of the light curve to peak are necessary to estimate the effect of the uniform and clumpy components.

(3) All recurrent nova systems at all wavebands in quiescent (e.g. Anupama & Mikołajewska 1999) and outburst phases need to be studied. Novae are an important Galactic system suited to the study of shock interaction with the ambient medium and its evolution over short time-scales, and multiple epochs.

ACKNOWLEDGEMENTS

We thank the reviewer, A. R. Taylor for a helpful review. We thank the staff of the GMRT that made these observations possible. GMRT is run by NCRA of the Tata Institute of Fundamental Research. We thank the Centre Director, NCRA for granting DDT time. We thank the AAVSO for all their valuable work. NGK thanks Prasad Subramanian for discussions and Dave Green for comments on the manuscript. PD acknowledges that this work is partially supported by the DST INSPIRE Faculty Fellowship award [IFA-13 PH 54] and performed at IISER, Bhopal.

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