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

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ABSTRACT

We present observations at 610 MHz and 235 MHz using the Giant Metrewave Radio Telescope (GMRT) of the recurrent nova V745 Scorpii which recorded its last outburst on 6 February 2014. 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 disk. 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 – novae – radio continuum:stars

1 INTRODUCTION

Recurrent novae are binary systems with the primary being a white dwarf and the secondary star being 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 magnitudes.

The last outburst of the recurrent nova V745 Sco, predicted by Schaefer (2010) to be in year 2013±1, was recorded on 6 Feb 2014 (Rod Stubbings, AAVSO special notice 380). The previous outbursts in V745 Sco were recorded on 10 May 1937 and 30 July 1989 (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 GMRT and combine it with 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 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 MHz and 610 MHz bands between 7 February and 7 September 2014. Bandwidth settings of 32 MHz at 610 MHz and 16 MHz at 235 MHz were used. A combination of Director’s Discretionary Time and regular TAC-
approved 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 minute run on an amplitude calibrator (3C286 or 3C48) followed by 3 minute and 30 minute runs on the phase calibrator (J1830–360) and V745 Sco. Most of the observing slots were ~ 2h in duration with ~ 1.5h on the nova and ~ 90 μJy rms noise on the final image at 610 MHz.

The data were converted from the native IAU 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″ × 5″ at 610 MHz and 20″ × 10″ 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 6 March 2014 detected a strong radio source at both 610 MHz and 235 MHz (Table [1]). 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 × 10^11 W Hz⁻¹ and 4 × 10^10 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.

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 ~ 10^12 Joule 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 × 10¹¹ Joule ie about 0.02% 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 Eqn. 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 Eqn 1 and Fig 3 top). The temporal variation in the optical depth due to uniformly distributed gas, τuniform and the clumpy gas, τclumpy is (Weiler et al. 2002).

\[ \tau_{\text{uniform}} \delta \] = \[ \tau_{\text{clumpy}} \delta \] = \[ K_2 K_3 \left( \frac{\nu}{5\text{GHz}} \right)^{-2} \left( \frac{t - t_0}{1\text{day}} \right) \] (1)

K2, K3, δ are determined from the fits to the light curve (see Table 3). The variation in both optical depths at three frequencies 235 MHz, 610 MHz and 1.4 GHz is shown in Fig. 3. As seen in the figure, \[ \tau_{\text{clumpy}} \] drops to one within five days following the outburst at all bands. \[ \tau_{\text{uniform}} \] 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 turnover 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 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

\[ \tau \] is 6 February 2014.
in the 1985 and 2006 outbursts of RS Ophiuchi are (1) The turn-on rapid fall in 
1940 2 Feb 1990 8.8 19 Oct 1989 1.28(0.18) VLA archives 
76 07 Oct 1989 1.96(0.36) VLA archives 
56 24 Sep 1989 3.17(0.22) VLA archives 
187 12 Aug 0.72 0.1 17.3(0.1) 17.86(0.16) - - - - 
60 18 Apr 2.52 0.17 15.3(0.11) 16.63(0.11) 4.3 0.9 30.7(1.4) 31.9(0.7) 0.24 
35 13 Mar 5.89 0.099 17.5(0.11) 18.33(0.09) - - - - 
86 03 Mar 3.38 0.07 18.06(0.19) 17.25(0.42) < - 43.1(0.98) 30.73(2.11) > -0.6 
27 05 Mar 5.11 0.13 15.91(0.13) 17.39(0.22) - - - - 
47 25 Mar 3.83 0.18 14.76(0.1) 16.27(0.16) 4.7 1.1 31.2(1.2) 30.1(0.4) 0.24 
101 18 May 1.17 0.14 16.41(0.14) 16.87(0.05) - - - - 
123 09 June 1.11 0.14 16.1(0.12) 17.58(0.07) - - - - 
154 10 July 0.99 0.099 13.42(0.22) 16.44(0.94) < - 28.7(1.6) 32.5(0.7) > 0.13 
129 17 Sep 0.48 0.12 16.6(0.07) 18.17(0.23) - - - - 
217 07 Sep 0.48 0.12 16.6(0.07) 18.17(0.23) < 5.7 - 26.3(1.8) 30.04(0.45) 

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 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 30 July 1989.

| $t-t_0$ (days) | Date       | Flux density at 610 MHz | Flux density at 235 MHz | $\sigma^{235}_{610}$ |
|---------------|------------|-------------------------|-------------------------|---------------------|
| V745Sco mJy/beam | J1830-360 mJy | bcksrc mJy | J1830-360 mJy | bcksrc mJy |
| 3  | 9 Feb 1989 | < 0.55 | - | 16.26(0.16) | 18.1(0.17) | - | - | - | - |
| 12 | 18 Feb 1990 | 1.07 | 0.14 | 16.41(0.14) | 16.87(0.05) | - | - | - | - |
| 27 | 05 Mar 1989 | 6.9 | 0.13 | 17.04(0.13) | 18.07(0.11) | - | - | - | - |
| 28 | 06 Mar 1989 | 43 | 0.9 | 30.9(0.09) | 29.44(0.3) & 0.49 |
| 35 | 13 Mar 1989 | 47 | 1.1 | 31.2(1.2) | 30.1(0.4) & 0.24 |
| 40 | 18 Mar 1989 | 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 | 25 Mar 1989 | 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 | 03 Apr 1989 | 3.38 | 0.07 | 18.06(0.19) | 17.25(0.42) | < 6 | - | 43.1(0.98) | 30.73(2.11) > -0.6 |
| 71 | 18 Apr 1989 | 2.52 | 0.19 | 18.08(0.19) | 19.2(0.4) | - | - | - | - |
| 86 | 03 May 1989 | 2.06 | 0.07 | 17.59(0.07) | 18.54(0.08) | - | - | - | - |
| 101 | 18 May 1989 | 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 | 09 June 1989 | 1.11 | 0.14 | 16.1(0.12) | 17.58(0.07) | - | - | - | - |
| 154 | 10 July 1989 | 0.99 | 0.099 | 17.5(0.11) | 18.33(0.09) | - | - | - | - |
| 187 | 12 Aug 1989 | 0.72 | 0.1 | 17.3(0.1) | 17.86(0.16) | - | - | - | - |
| 217 | 07 Sep 1990 | 0.48 | 0.12 | 16.6(0.07) | 18.17(0.23) | < 5.7 | - | 26.3(1.8) | 30.04(0.45) |

3.3 Comments on evolution of novae from opacity variation

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 $\tau_{clumpy}$ 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% 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.
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)]. The later 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 ($\sim 1000 \, km \, s^{-1}$, $\geq 10^{-6} \, M_\odot \, yr^{-1}$) blown by the white dwarf which they refer to as accretion winds. The accretion winds would stabilise the system and the binary can continue to evolve as a single degenerate system [Hachisu, Kato, & Nomoto 1996]. The accretion rates for V745 Sco and RS Ophiuchi were estimated to be $2 \times 10^{-7} \, M_\odot \, yr^{-1}$ (using a recurrence timescale of 25 years) and $1.2 \times 10^{-7} \, M_\odot \, yr^{-1}$ [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 disk 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 ($< \, \text{few times} \, 10^{-7} \, M_\odot \, yr^{-1}$) 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 ambiguity 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

### Table 3. Model outputs. The spectrum is assumed to have a spectral index of $\alpha = -0.5$. Emission measure of absorbing gas when the optical depth is one. The electron temperature is assumed as $10^{5} \, K$. N is the number of detections, $t_{\text{peak}}$, $S_{\text{peak}}$, $t_{1%}$ refer to the day on which peak emission occurred, peak emission strength and the day on which the emission was 1% of peak emission. $\beta$ is the temporal decay index, $K_{2}$, $\delta_{\text{uniform}}$, $K_{3}$, $\delta_{\text{clumpy}}$, $\chi^{2}_{\text{red}}$, $\text{EM}_{\text{peak}}$ are the constants from Eq. 1.

| Nova          | Outburst epoch | $\nu$   | N | $t_{\text{peak}}$ | $S_{\text{peak}}$ | $t_{1%}$ | $\beta$ | $K_{2}$ | $\delta_{\text{uniform}}$ | $K_{3}$ | $\delta_{\text{clumpy}}$ | $\chi^{2}_{\text{red}}$ | $\text{EM}_{\text{peak}}$ cm$^{-3}$ 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               | 8.7     | -1.4    | -2.9   | -3                       | -6.3   | 4                        | $6 \times 10^{6}$          |
| 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                    | $6 \times 10^{6}$          |

1 Parameters from the multi-frequency 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)].

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 ($\sim 1000 \, km \, s^{-1}$, $\geq 10^{-6} \, M_\odot \, yr^{-1}$) blown by the white dwarf which they refer to as accretion winds. The accretion winds would stabilise the system and the binary can continue to evolve as a single degenerate system [Hachisu, Kato, & Nomoto 1996]. The accretion rates for V745 Sco and RS Ophiuchi were estimated to be $2 \times 10^{-7} \, M_\odot \, yr^{-1}$ (using a recurrence timescale of 25 years) and $1.2 \times 10^{-7} \, M_\odot \, yr^{-1}$ [Hachisu & Kato 2001]. Combining our results with the theoretical arguments, we infer the following:

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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 ($< \, \text{few times} \, 10^{-7} \, M_\odot \, yr^{-1}$) 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 ambiguity 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
Recurrent nova evolution from radio synchrotron emission

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 ~ day 23 in 2014 and ~ day 18 at 1.4 GHz in the 1989 outburst. Our model fit predicts that the 1.4 GHz emission would have peaked ~ day 10 in 2014. In RS Ophiuchi, the radio synchrotron emission at 1.4 GHz turned on 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 disk 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 timescales 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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