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Studies of novae at GMRT frequencies

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Abstract. The Giant Metrewave Radio Telescope (GMRT) which operates at wavelengths longer than 20 cm (frequencies $\leq$ 1.4 GHz) has been used to search for radio emission from Galactic novae systems since 2002. Of the 11 Galactic novae observed with GMRT, radio continuum emission has been detected in two of the systems whereas atomic gas associated with two systems has been imaged and studied in the 21 cm signal of HI. The two novae studied in the radio continuum with the GMRT are the remnant of GK Persei, a classical nova which had an outburst in 1901 and RS Ophiuchi, a recurrent nova following its last outburst in 2006. Combining the GMRT data on the classical nova GK Persei with VLA data at earlier epochs resulted in concluding that the nova remnant was undergoing a secular decrease in its flux density and in its adiabatic phase of evolution (Anupama & Kantharia 2005). RS Ophiuchi was observed at 1280, 610, 325 and 240 MHz with the GMRT days after its outburst and detected at all the observed frequencies. The near-simultaneous monitoring of its flux density at the low GMRT frequencies, resulted in the study of its spectral index which was indicative of synchrotron emission at all epochs (Kantharia et al. 2007). A supernova model resulted in a reasonable fit to the observed light curves; in particular the late appearance of emission at the lower GMRT frequencies due to the foreground clumpy, ionized, thermal circumbinary material. Comparison of these results with the previous outburst indicated that the densities of this clumpy medium had reduced making it optically thin to GMRT frequencies in 2006 (Kantharia et al. 2007).

It is important to complement the higher radio frequency studies with observations at GMRT frequencies since these study different regions and physics of the nova system. Studies at GMRT frequencies can result in insights on the shock physics, distribution and density of the circumbinary material or planetary nebula, magnetic field generation and the spectral index evolution. Since the evolution of a nova system is faster than a supernova and novae are more numerous; these can be studied over shorter

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timescales. A sensitivity limit of 1 mJy can detect radio emission at GMRT frequencies upto a distance of 10 kpc, if the non-thermal luminosity of the novae system is 10^{13} W Hz^{-1}. Out of the total of about 33 novae detected in the radio bands, 9 have shown the presence of non-thermal emission in their spectra and 4 of these are recurrent in nature. GMRT frequencies are ideal to observe the non-thermal emission from the recurrent nova population as the ejecta expands driving shocks into the dense circumbinary material from the giant companion. An important motivation for studying the non-thermal radio emission from recurrent novae is to interrogate any evolutionary connection to the lack of detectable radio emission from type 1a supernova systems which recurrent novae are believed to evolve into and subsequently lend support to this model.

Keywords : (stars:) novae, cataclysmic variables – (stars:) white dwarfs – radio continuum: stars

1. Introduction

Novae form an important sub-class of transient objects in our Galaxy and other galaxies. Since novae are binary systems of low to intermediate mass stars, nova outbursts are expected to be fairly frequent with estimates of 30 novae per year (Shafter 2002). However the mean detected nova rate is 3 per year (Warner 2008) while the observable number is estimated to be 12 per year (Liller & Mayer 1987). These objects contribute to enriching the interstellar medium (ISM) with heavy isotopes of ^{13}C, ^{15}N, ^{22}Na and ^{26}Al. The matter input to ISM from novae is a small fraction of that input by red giants stars but since such specific isotopes are a result of the thermonuclear reaction on the surface of the white dwarf, it allows an indirect study of the Galactic distribution of novae using spectral signatures of these isotopes (Iyudin et al. 2002). Novae allow us to study several physical parameters of the binary system and the environment using data at wavebands ranging from gamma rays to radio bands; all of them contributing to giving a complete picture of the system and its interaction with the surrounding medium. A nova ejects about 10^{-4} – 10^{-8} $M_\odot$ of mass during an outburst which has a typical energy of 10^{38} to 10^{43} ergs.

Novae are classified into two different populations based on their location in the Galaxy - the disk population and the bulge population (see Fig. 1) and the detected novae show bias towards the first Galactic quadrant (Duerbeck 1990). Of the total of about 400 novae known in our Galaxy, around 33 novae have been detected in the radio bands (Fig. 1). Nine of these have shown the presence of non-thermal synchrotron emission either inferred through high brightness temperatures or the spectral index. The distribution of the radio novae and novae from which non-thermal emission has been detected are shown in Fig. 1. Only three of these have been observed at frequencies $\leq$ 1.4 GHz i.e. GMRT frequencies. Out of these two have been observed with GMRT, namely GK Persei (Anupama & Kantharia 2005) and RS Ophiuchi (Kantharia et al. 2007).

While the high radio frequency (> 1.4 GHz) emission is generally well-fitted by free-free brehmstrahlung from the hot (T=10^4 K) expanding ($v_{ej} \geq$ few1000 km s^{-1}) ejecta, the low radio frequency ($\leq$ 1.4 GHz) emission requires another mechanism which is not thermal in nature. Synchrotron emission from the interaction of the expanding shock with the circumbinary material or the interstellar material (in case of remnants) well explains the observed emission at GMRT frequencies. In this article, we describe the radio observations of novae at GMRT frequencies ($\leq 1.4 GHz$), what we have learnt from these, describe the systems which have been studied with GMRT and comment on which systems to target to optimise the results at these low radio frequencies in terms of understanding the immediate environs of a nova.

Roy et al. (2012, this Volume) and Seaquist & Bode (2008) give a comprehensive summary of radio studies of novae. Here we limit the discussion to studies at GMRT frequencies of the synchrotron component and their results. We use $S \propto \nu^{\alpha}$ throughout the paper and refer to frequencies $\leq$ 1.4 GHz as GMRT frequencies.

2. Non-thermal synchrotron emission from novae

Of the 400 or so Galactic novae that are known, radio emission has been been detected from around 33 novae with 9 showing the presence of a non-thermal synchrotron component in their total radio emission. 10 out of the total 400 Galactic novae are recurrent in nature with multiple recorded outbursts and four of these have shown the presence of non-thermal emission in their spectra. The distribution of these radio novae is shown in Fig. 1.

Radio emission below 1 GHz has been detected from three novae systems - the classical nova GK Persei (Reynolds & Chevalier 1984; Seaquist et al. 1989; Anupama & Kantharia 2005), the classical nova V1370 Aquila (Snijders et al. 1987) which had a reported outburst in 1982 and the recurrent nova RS Ophiuchi following its 2006 outburst (Kantharia et al. 2007). While non-thermal synchrotron emission was considered as a strong possibility for V1370 Aquila, Snijders et al. (1987) comment that the data did not give compelling evidence for the synchrotron origin. In the case of RS Ophiuchi, observations at several frequencies below 1 GHz and at several epochs enabled the calculation of the non-thermal spectral index which was found to vary from -0.1 to -1. These estimates had minimal corruption due to thermal emission. Although Kantharia et al. (2007) gave the first well-sampled light curves at GMRT frequencies following a nova outburst and estimated the spectral index evolution which supported the synchrotron origin, they were not the first to detect synchrotron emission from a nova system.

Hjellming et al. (1986) reported that the emission from the 1985 outburst of the recurrent nova RS Ophiuchi consisted of a non-thermal component. They observed that the development of the radio emission of RS Ophiuchi was different than that observed for classical novae and hence suggestive of a different emission mechanism. Hjellming et al. (1986) noted that the rise in the radio emission was rapid and had high brightness temperature; both of which, they suggested, can be explained by a combination of synchrotron emission for the low frequency component ($\sim$ 1.4 GHz) and thermal emission at higher radio frequencies. This was supported by Taylor et al. (1989), who made VLBI observations of RS Ophiuchi following its 1985 outburst and detected a linear multi-component radio source indicating a non-spherical mass ejection. Although the spectrum they observed had an index of -0.1, the estimated brightness temperature was in excess of 10^7 K which did not agree with the observed X-ray flux if they had a thermal origin and the non-thermal contribution to the radio emission was inferred. Following the 2006 outburst in RS Ophiuchi, O'Brien et al. (2006), detected and imaged an asymmetric, expanding shock using VLBI and MERLIN. The radio emission was non-thermal in nature and similar to the previous outburst in 1985. Eyres et al. (2009) reported multi-telescope, multi-frequency observations which also demonstrated the presence of both thermal and non-thermal emission in the radio emission. Bode & Kahn (1985) estimated an outburst energy for the 1985 outburst of RS Ophiuchi as 8×10^{42} ergs and concluded that the total energy content in the relativistic electrons was only 0.02% of the total energy output.

The nine novae system in which non-thermal emission has been inferred are RS Ophiuchi (Hjellming et al. 1986; Taylor et al. 1989; O'Brien et al. 2006; Kantharia et al. 2007), V1370 Aquila (Snijders et al. 1987), ASM 2000+25 (Hjellming et al. 1988), QU Vulpeculae 1984 (Taylor et al. 1988), V407 Cyg (Krauss et al. 2010; Mioduszewski et al. 2012), V445 Puppis (Rupen, Dhawan & Mioduszewski 2001a; Rupen, Mioduszewski & Dhawan 2001b), V2672 Ophiuchus (Krauss Hartman, Rupen & Mioduszewski 2009), SS Cygni (Körding et al. 2008) and the remnant of GK Persei (Reynolds & Chevalier 1984; Seaquist et al. 1989; Anupama & Kantharia 2005). From the detections so far, about 30% of the novae detected in the radio bands have shown the presence of synchrotron emission in their spectra. GMRT is one of the best instruments to study the non-thermal radio component and a concerted effort towards rapidly obtaining high quality data will be useful. This in turn, will help study the evolution of the spectrum of the non-thermal emission from these objects, understand the shock interaction with the circumbinary material and infer the variation in the densities of the foreground red giant wind when successive outbursts are monitored.

Emission at GMRT frequencies can be detectable from shock interaction with the circumbinary material, ejecta and the ISM. Soon after a nova outburst, the forward shock interacts with the dense circumbinary material, expands and encounters the ISM driving a reverse shock into the nova ejecta. The radio emission at GMRT frequencies resulting from the shock interaction with the circumbinary material fades over timescales of days or months. This phase of evolution in a nova appears to be similar to the well-studied and more energetic early phase in supernovae but has a lower power and faster evolution. RS Ophiuchi was one such system where GMRT studied its early light curve evolution at several frequencies (Kantharia et al. 2007). Non-thermal emission from other systems like V445 Puppis have been studied with other telescopes. The second scenario is where the ejecta expands into and the shock interacts with the surrounding ISM which could also be a planetary nebulae from an earlier phase of evolution giving rise to what is known as 'nova remnant' emission. This phase appears to bear similarity to the more energetic supernova remnant phase of evolution of the system but is characterised by lower energies and faster evolution. GK Persei is a classical nova system in which such a remnant is detected which emits synchrotron emission from optical to radio wavelengths. GMRT has detected and studied the radio emission from this system (Anupama & Kantharia 2005).

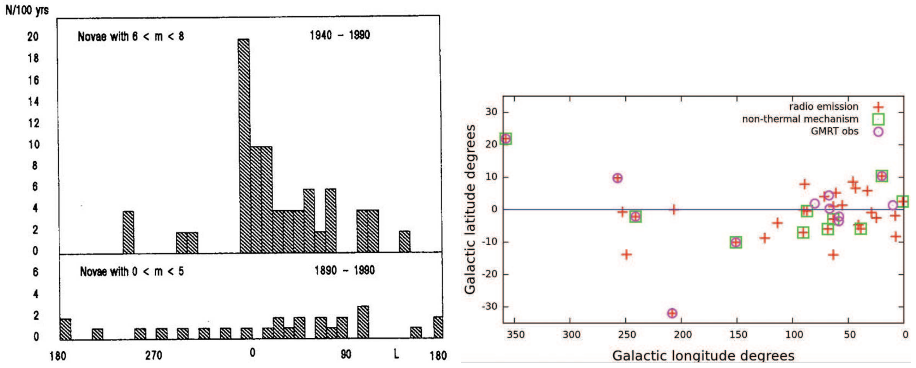

Figure 1. Left panel: Galactic distribution of all classical novae till 1990. Figure taken from Duerbeck (1990). Two populations of novae are postulated - the closer disk population and the faraway bulge population which peaks near zero longitude. The latter population is mostly concentrated in the first quadrant which Duerbeck (1990) explains as a bias due to better monitoring. The top plot is for fainter novae and lower panel is for brighter novae. Right panel: Distribution of novae detected at radio wavelengths in Galactic coordinates. The squares denote the novae which have shown the presence of synchrotron emission in their spectra and are the ones under discussion here. The open circles indicate the novae which have been targeted with GMRT and crosses are the radio novae. Note that most of the novae detected at radio wavelengths lie in the first quadrant of the Galaxy similar to the distribution of classical novae shown in the left hand side panel.

2.1 What can we learn from observations at GMRT frequencies?

As mentioned above, GMRT frequencies are excellently placed to study the non-thermal radio emission following a nova outburst and when combined with the predominantly thermal emission at higher radio frequency can complete the radio picture of a nova event. When combined with data from X-rays to radio wavelengths; a comprehensive picture of the physical conditions in the circumbinary gas such as density, temperature and magnetic field can be obtained.

GMRT is an ideal instrument to study the behaviour of the early light curve of the non-thermal emission from a nova outburst. Moreover it can also be used to monitor any non-thermal emission which might appear at later times due to shock interaction with the ISM or ejecta. Since the contribution of thermal free-free emission at GMRT frequencies is insignificant, the spectrum of the non-thermal emission can be studied by simultaneous or near-simultaneous observations at these low frequencies and a detailed picture of the evolution of the non-thermal spectral index can be derived. The multi-frequency light curves can then be modelled to understand the physical parameters of the emitting and the absorbing medium. This was done for RS Ophiuchi using GMRT by Kantharia et al. (2007). While the results were interesting, suggesting that the emission was similar to radio emission from a young supernova; better sampling of the light curves at all the observed GMRT frequencies would have helped refine the model better.

Since the best angular resolution possible with GMRT is a few arc seconds; it is not possible to resolve the shock or remnant as is possible, for example with MERLIN, VLBI and JVLA at higher frequencies (O'Brien et al. 2006; Taylor et al. 1989; Mioduszewski et al. 2012). GMRT can contribute significantly to the study of the integrated behaviour of the non-thermal emission following the nova outburst and construct light curves as inputs for modelling of these systems. GMRT can study the detailed emission from a nova remant which is a few arcminutes across with high angular resolution. However such nova remnants are rare with GK Persei being the only such remnant known.

Another important aspect which can be studied at GMRT frequencies concerns the environment of recurrent novae if they are progenitors of type 1a supernovae. No radio emission has been detected from any type 1a supernova (Hancock, Gaensler & Murphy 2011) which has raised questions on the missing circumbinary material and the fate of the material in a recurrent nova system. The early evolution of the radio emission from recurrent novae can be studied at GMRT frequencies to understand the evolution of the circumbinary material. Moreover since non-thermal radio emission has not been detected from all recurrent novae; the reasons can be further explored.

Radio flares in the form of sudden jumps in the intensity are observed during the evolution of the radio light curve. A 5 GHz flare was recorded by Spoelstra et al. (1987) following the 1985 outburst of the nova RS Ophiuchi. The authors drew analogy with solar flares and suggested that the flare arises in a region of magnetic flux reconnection. Such flares were noted for V445 Puppis (http://www.aoc.nrao.edu/ mrupen/XRT/V445Pup/v445pup.shtml) and are also seen in the light curve of RS Ophiuchi at 610 MHz and 325 MHz (see Fig. 2). Good temporal monitoring with GMRT can result in capturing many such flares and understanding the magnetic field reconnection and enhancements at these sites.

Since the emission at GMRT frequencies is non-thermal in nature; modelling its spectral and temporal evolution involves evolving the observed spectrum with the thermal gas which is either mixed with the relativistic particle distribution or is foreground leading to free-free absorption of the low frequency synchrotron spectrum. The thermal gas can be homogenous or clumpy in nature and these modify the synchrotron emission reaching us. Such models have been developed for explaining the early evolution of radio emission from a supernova (Weiler et al. 2002). These models include an expanding shock in the circumstellar material which has both a uniform density component and a clumpy component. Such models appear to be well suited to explain the non-thermal emission following a nova explosion and hence was done for RS Ophiuchi (Kantharia et al. 2007). A reasonable fit to the light curve data was obtained. The main source of opacity was found to be the clumpy component in the foreground thermal circumbinary material. The typical temperature of this material is about 10^4 K and wind velocities are 20 km s^{-1}. It is interesting that the evolution of the low frequency radio emission from novae is similar to the radio emission observed from supernovae. However, the model has been fitted to data on a single nova, RS Ophiuchi and the model light curve did not explain the evolution at all the GMRT frequencies. Thus, it would clearly help to have data on many more systems which would help refine the model and introduce any changes in the model which might be specfic to a nova environment such as the binary nature of the central system; opacity due to thermal gas mixed with the relativistic particle population etc.

Totally 11 novae have been observed with GMRT (see next sections for details). Two of these have been detected in radio continuum and subsequently studied in great detail. The results have been interesting and encouraging and clearly novae systems need to be systematically followed at GMRT frequencies to further enhance our understanding of these systems.

Thus in summary, monitoring promising novae following outburst at GMRT frequencies can result in important insights into the system and particle acceleration, in particular, (1) evolution of the low frequency radio emission from novae can be studied consequently helping understand the diffusive shock acceleration (2) models which explain the evolution of non-thermal emission following a nova/supernova outburst can be refined (3) better understanding of the clumpiness and physical properties of the circumbinary material can be obtained (4) the progenitor theory for Type 1a supernovae can be explored by studying the radio emission from recurrent novae at GMRT frequencies.

3. GMRT observations

The Giant Metrewave Radio Telescope (GMRT; Swarup et al. (1991)) consisting of 30 antennas, each of diameter 45m spread over a 25 km region is located about 80 km north of Pune. The Y-shaped array results in 435 snapshot visibilities and rotation of earth ensures good uv coverage for extended radio sources. While 14 antennas are located within a kilometre, inside the main GMRT campus, five are located along a southern arm, six are located along a western arm and five are lcoated along an eastern arm. The telescope operates at five wavebands namely 21 cm, 49 cm, 90 cm, 128 cm and 200 cm with the maximum bandwidth possible at each band being 32 MHz. GMRT is a prime focus instrument with all the feeds mounted on a turret at the focus. GMRT always operates in the spectral line mode enabling better excision of radio frequency interference (RFI) and bandpass calibration of the data is required for both continuum and spectral line datasets.

For almost all the observations, the GMRT observing session started and ended with a short run on the amplitude calibrator which was generally 3C48, 3C147 or 3C286. This calibrator, also, in most cases doubled as the bandpass calibrator since it was a strong source and thus minimised the observing time on the bandpass calibrator. In case of spectral line observations, a bandpass calibrator was observed more frequently (about once in two hours) through the observing run to enable better correction of the gain variations in the bandpass as a function of time. After the first run on the amplitude calibrator; the observations alternated between the target nova and a phase calibrator. This ensured reasonable gain calibration of the nova data which was improved using self-calibration in later stages of the analysis.

The GMRT interferometric data analysis was carried out in NRAO AIPS.[1] Initially data on

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

a single spectral channel which were relatively free of radio frequency interference (RFI) were selected, gain cailbrated and bad data excised in an iterative procedure. In the second major step of analysis, the data on the calibrator were used to estimate the bandpass gains and then edit bad data on all the sources. The spectral channel data were bandpass-calibrated and averaged. Bandwidth smearing in the outer parts of the primary beam limited the number of channels that could be averaged at any GMRT band. This resulted in a continuum database with several channels. One of the channels was selected and the amplitude and phase calibrator data were gain calibrated and the data rid of remnant RFI. The generated gain tables were applied to the target source; bad data edited and the target field was imaged. All the radio continuum data were generally imaged using wide-field options in AIPS where the primary beam was divided into several smaller fields with independent phase centres. The number of fields covering the primary beam was a function of the waveband with the largest number of fields at 240 MHz (49) and smallest number of fields at 1420 MHz (9). These images were then used to generate self-calibration gain tables and iteratively applied to the data to generate better images. The continuum images, thus generated, were ready for further analysis.

In case of spectral line data, the bandpass gains were calibrated more frequently and the gain tables were applied to the target source. After removing the continuum emission, the image cubes were generated for the line data. Moment maps were generated from these line cubes which were then used for further analysis. More details of some of the observations can be found in the published papers (Anupama & Kantharia 2005; Kantharia et al. 2007; Roy et al. 2012b).

GMRT has observed several classical and recurrent novae - a summary of the novae observed and the observations conducted till date with GMRT are given in Tables 1 and 2. As can be seen from Table 1, the distances to these novae range from 0.5 to 13 kpc. Three recurrent novae have been observed and four of the novae appear to be bulge novae. Most of the GMRT observations were multi-frequency ones. Radio emission has been detected from two of the observed systems. The rest of the systems have limits listed in Table 2. The upper limits on the luminosity at 610 MHz range from 0.04×10^{12} to 20×10^{12} W Hz^{-1}. GK Persei was observed using GMRT in 2002 (Observing Cycle 2) and 2005 (Observing Cycle 8) - the data from 2002 were analysed and presented in Anupama & Kantharia (2005) and Kantharia, Anupama & Subramanian (2005). The data from 2005 remain to be analysed. RS Ophiuchi was observed in 2006 soon after its outburst using slots alloted from Director's Discretionary Time and the results were presented in Kantharia et al. (2007) and Eyres et al. (2009). Four novae were observed in the dual frequency (610/240 MHz) mode available at GMRT during GMRT Observing Cycle 16 in 2009. Only a quick analysis of the data on the four classical novae (V2491 Cygni, V459 Vulpeculae, V2468 Cygni, V2467 Cygni) was done at 610 MHz. A careful analysis is pending. The 240 MHz data remain to be analysed. The environs of the classical nova V458 Vulpeculae were observed in the 21cm HI line in the same observing cycle. The data have been analysed and presented in Roy et al. (2012b). The Helium nova V445 Puppis was observed using Director's Discretionary Time in 2009. U Scorpii and T Pyx were both observed using Director's Discretionary Time in 2010 and 2012 respectively.

As listed in Table 2, radio continuum emission at GMRT frequencies were detected from two

Table 1. Details of the novae observed with GMRT

No	Nova	Type	Dist.[a]	Galactic		Ht.	Outburst
			kpc	longitude	latitude	kpc	
1	GK Persei	classical	0.5	150.9553	−10.1042	0.03	1901
2	RS Ophiuchi[b]	recurrent	1.6	19.7995	10.3721	1.2	11/2/2006
3	V458 Vulpeculae	classical	13	58.6331	−3.6171	0.8	8/8/2007
4	V445 Puppis[b]	classical (He)	8.2	241.1238	−2.1914	0.3	28/11/2000
5	U Scorpii[b]	recurrent	12	357.6686	+21.8686	4.8	28/1/2010
6	T Pyxidis	recurrent	1	257.2072	+09.7067	0.2	14/4/2011
7	V2491 Cygni	classical	10.5	067.2287	+04.3531	0.8	10/4/2008
8	V459 Vulpeculae	classical	4	058.2138	−02.1673	0.2	25/12/2007
9	V2468 Cygni	classical	14	066.8084	+00.2455	0.06	8/3/2008
10	V2467 Cygni	classical	3	080.069	+01.8417	0.09	15/3/2007
11	KT Eridanus	classical	7	207.9863	−32.0202	4.3	25/11/2009

Notes: (a) Distances to the novae are from the literature.
(b) The mass of the white dwarf is estimated to be close to the Chandresekhar mass limit.

nova systems, namely GK Persei and RS Ophiuchi. The results on the nova V445 Puppis were perplexing as discussed later. For the detected novae, the radio continuum emission at GMRT frequencies allowed study of the evolution of the low frequency radio spectrum and the physical conditions in these systems. While no radio continuum emission has been detected from rest of the systems observed with GMRT down to some limiting flux density; the environs of two novae namely GK Persei and V458 Vulpeculae have been studied in the 21cm spectral line of Hɪ using GMRT. In the following sections, we briefly describe the results of the GMRT observations of the three novae which have led to interesting new insights into the systems and the perplexing results on the fourth nova.

3.1 The classical nova: GK Persei

GK Persei, a classical nova system consisting of a white dwarf and an evolved late type (K2) companion star with an orbital period of 1.904 days had a recorded outburst in 1901. Since the last 30 years, the nova has been exhibiting dwarf nova-like outbursts over a few years timescale (e.g. Evans et al. 2009). This was the first system from which light echoes were detected following the explosion (Ritchey 1901) whereas the expanding ejecta was detected 15 years later (Couderc 1939). The evolution of the optical and radio emission upto 1988 were extensively discussed by Seaquist et al. (1989). Bode et al. (1987) reported the detection of extended emission in the far infrared from a 30’ region ($\sim$ 6 pc for a distance of 500 pc), which they interpreted as being from the planetary nebula surrunding the GK Persei system. This was also detected in the 21cm spectral line of HI in emission (Seaquist et al. 1989; Anupama & Kantharia 2005).

GMRT time was requested and allocated in 2002 to observe this enigmatic nova in the radio

Table 2. GMRT Observations of Novae. Column 4 labeled 'Det?' refers to detection of radio continuum emission from the nova system. All the novae observed with GMRT have been observed in the 610 MHz band so the date of observation, flux density or limits listed here pertain to that. Luminosity at 610 MHz is in units of 10^{12} W Hz^{-1}. Several novae have been observed at GMRT frequencies as listed in column 3.

No	Nova	ν MHz	Det?	Dist* kpc	610MHz 3σ mJy	Date of Obs	L_{610} W Hz^{-1}
1	GK Persei	325, 610,1280,HI[a]	Y	0.5	21.8[1]	5/9/2002	0.65
2	RS Ophiuchi	240,325,610	Y	1.6	48.9[2]	13/3/2006	15
3	V458 Vulpeculae	1420, HI[a]	N[b]	13	< 1[3]	11/6/2009	< 20.2
4	V445 Puppis	610,1280	N	8.2	< 0.36[4]	28/10/2009	< 2.89
5	U Scorpii	610,1280	N	12	< 0.3[5]	11/2/2010	< 5.17
6	T Pyxidis	610	N	1	< 0.3[6]	18/3/2012	< 0.036
7	V2491 Cygni	610,240	N	10.5	< 0.5[@,7]	21/6/2009	< 6.59
8	V459 Vulpeculae	610,240	N	4	< 2.0[@,7]	21/6/2009	< 3.83
9	V2468 Cygni	610,240	N	14	< 0.5[@,7]	21/6/2009	< 11.7
10	V2467 Cygni	610,240	N	3	< 1.6[@,7]	21/6/2009	< 1.72
11	KT Eridanus	610	N	7	< 1.0[8]	10/1/2010	< 5.86

Notes: * - Distance estimates obtained from literature. @ - Quick analysis results. (a) This nova was observed in the HI 21cm spectral line. (b) HI was detected near V458 Vulpeculae.

1. Anupama & Kantharia 2005; 2. Kantharia et al. 2007; 3. Roy et al. 2012a; 4. Ashok, Kantharia & Bannerjee (in preparation); 5. Anupama et al. (in preparation); 6. Roy et al. 2012b; 7. Eyres et al. (in preparation); 8. O'Brien et al. 2010

continuum and 21cm line of atomic hydrogen. These were the first GMRT observations of a nova system. GMRT observed and detected the nova remnant in the radio continuum in the 325 MHz, 610 MHz and 1280 MHz bands. Moreover 21cm HI emission was also detected from the planetary nebula. A detailed optical and radio study of the remnant emission was presented by Anupama & Kantharia (2005). The radio emission was found to have the same angular extent as the optical and was enhanced along the south-west boundary as also observed in the optical. The proper motion of the nova well explains the compressed region as the nova remnant rams into the interstellar medium.

The main results of the study at GMRT frequencies combined with VLA archival data at higher frequencies presented in Anupama & Kantharia (2005) and Kantharia et al. (2005) can be summarised to be: (a) A steep spectrum at low frequencies ($\alpha_{325}^{1280} \approx -0.85$) detected in epoch 2002. The low frequency spectrum ($\alpha_{325}^{600} \approx -0.4$) in 1985 (Seaquist et al. 1989) was relatively flat. No data are available for epochs between 1985 and 2002 at these low frequencies. (b) The high frequency spectral index ($\alpha_{1400}^{4800} \approx -0.7$) from 1985 to 1997 was constant. An annual secular decrease of 2.1% explained the lower flux densities observed at both the frequencies in 1997. (c) The flux density at 610 MHz remained unchanged between 1985 and 2002 while the radio emission at 325 MHz was stronger in epoch 2002 as compared to 1985. (d) Presence of more than one electron population was considered from the break in the spectrum and the offset between the radio peaks at 325 MHz and higher frequencies. (e) equipartition arguments give an estimate of the minimum energy in relativistic particles of $10^{34}\eta^{4/7}$ Joules which is much lower than $10^{41}\eta^{4/7}$ Joules which is typical for particles accelerated in supernova remnants like Cas A. The contribution to cosmic ray flux from novae is not significant as has been known from other studies. η is the ratio of energy contained in protons and electrons. (f) Extended ($\sim 15'$) HI emission near 5 km s^{-1} was detected surrounding the nova and coinciding with part of the planetary nebula (Bode et al. 1987; Seaquist et al. 1989). Absence of absorption from this nebula towards a background source indicated that the spin temperature of the gas was more than 150 K.

The GMRT observations thus gave interesting insights into the evolution of the nova remnant and further pointed out the similarity in its evolution to a supernova remnant.

3.2 The recurrent nova: RS Ophiuchi

RS Ophiuchi, the recurrent nova binary consists of a white dwarf and a M type giant secondary with an orbital period of 455.7 days. The last recorded outburst of this system was on 11 February 2006. The outburst triggered extensive monitoring in several wavebands resulting in well sampled data from X-rays to radio bands. Since this nova had an outburst in 1985 which had also been well-studied at several wavebands; combining those results from the ones resulting following the 2006 outburst was important in advancing our understanding of the outburst and the environment in which it happened.

Radio emission was detected from this system on day 4.5 at 6 GHz using MERLIN and the multifrequency emission recorded in all subsequent epochs had contributions from both thermal and non-thermal emission (Eyres et al. 2009). O'Brien et al. (2006) detected and imaged an expanding shock from the nova system starting from day 13. They found that the non-thermal emission was more extended with bipolar morphology and rapidly expanding. The recurrent nova was also monitored at the GMRT frequencies with the first detection recorded on day 11 in the 1280 MHz band (49.5 mJy). Observations in the 610 MHz band on day 20 detected a radio source of strength 48.4 mJy at the nova position. The radio emission from the nova system was observed and detected on day 38 at 325 MHz (43.7 mJy) and on day 45 (54.2 mJy) at 240 MHz. The radio light curves at 610 and 325 MHz were fairly well-sampled till day 351 and day 284 respectively when the flux densities had dropped to 3.9 mJy and 6.3 mJy respectively. Kantharia et al. (2007) & Eyres et al. (2009) presented the results and it was the first time that the time evolution of the flux density of the nova at low GMRT frequencies of 325 and 610 MHz was followed in such detail as shown in Fig. 2. Such monitoring found that the spectral index between 325 and 610 MHz varied from -0.1 near maximum to -1 around day 220.The non-thermal emission at GMRT frequencies seems to have dropped rapidly between days 53 and 93 when the shocks were expected to have cleared the circumbinary material. However, GMRT data had infrequent sampling around that time to allow a more quantitative statement. This also allowed model fitting to the light curve data to derive the physical properties of the nova system. Kantharia et al. (2007) fitted the model given in Weiler et al. (2002) to the available GMRT data. This model is used to

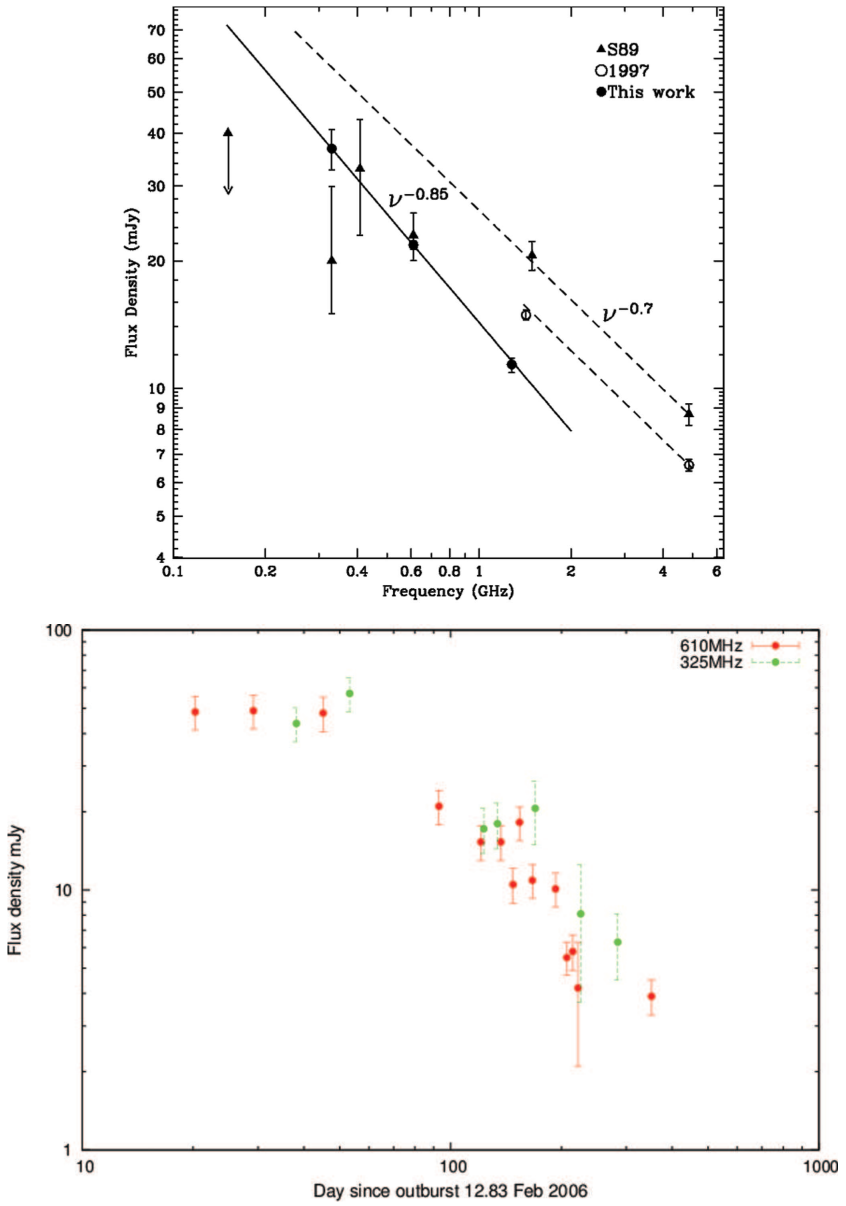

Figure 2. Top:Radio spectrum of GK Persei from Anupama & Kantharia (2005). Notice the secular evolution of the spectrum between 1.4 and 4.8 GHz which left the spectral index unchanged at −0.7. The spectrum between 325 and 1280 MHz has a spectral of index −0.85. Bottom: Light curve at 610 and 325 MHz of the recurrent nova RS Ophiuchi. Data taken from Kantharia et al. (2007). Notice the flat maximum and step-like evolution of the light curve at 610 MHz and the flare seen at 325 MHz near day 170.

fit the evolution of non-thermal radio emission from supernovae and is thus relevant for the nova emission at low radio frequencies.

The Weiler et al. (2002) model includes the effect of the foreground homegenous and clumpy material through which the shock is expanding. Kantharia et al. (2007) found that the best fit for RS Oph was when the optical depth modifying the observed non-thermal emission was due to the clumpy material. As the ejecta expanded, the opacity due to clumpiness in the CBM dropped rapidly. No radio emission down to a 3σ limit of 12 mJy at 325 MHz was detected on day 56 following the nova outburst in 1985 (Spoelstra et al. 1987), whereas a radio source of strength 57 mJy was detected on day 53 following the 2006 outburst. O'Brien et al. (2006) showed that the outbursts in 1985 and 2006 were similar in nature with both showing a linear extension in the east-west direction; which made the environment responsible for the different behaviours observed at GMRT frequencies. Using radiative transfer arguments, Kantharia et al. (2007) inferred that the density of the foreground stellar wind in 2006 was about 30% of that in 1985 rendering the 325 MHz emission visible at an early time.

Thus the main results of the GMRT study of the low radio frequency emission from the RS Ophiuchi system can be summarised to be: (a) Detection of non-thermal emission at frequencies < 1 GHz. (b) GMRT observations missed the rising part of the light curves. The emission at the GMRT frequencies was detected near the peak of the light curve. (c) Flare-like enhancement in the flux density observed at 610 MHz on day 154 and at 325 MHz on day 170 as seen in Fig. 2. (d) The overall evolution of the radio synchrotron emission at GMRT frequencies is explained by decreasing free-free absorption in the clumpy foreground CBM. (e) The 610 MHz light curve which is the best sampled light curve at GMRT frequencies shows a peculiar evolution with a flat peak and a fading marked with plateaus of emission (see Fig. 2). This could possibly be due to appearance of emission components that O'Brien et al. (2006) noticed in their high resolution images. (f) The similarity of the evolution of the radio emission in the 1985 and 2006 outburst suggests that the difference in the detectability of the radio emission at lower frequencies at similar epochs is due to different free-free absorption in the two epochs i.e. different densities in the foreground material.

Thus, early observations at low radio frequencies and good sampling of the data at GMRT frequencies before the emission faded resulted in interesting insights in the spectrum of the non-thermal emission and its evolution with time in addition to the change in the density of the circumbinary material compared to the earlier outburst. Although the model did not explain all the characteristics of the observed data such as the decline in the flux density at 610 MHz or the flares, the fit was able to explain the overall evolution at GMRT frequencies especially the late detection of lower frequencies. Clearly, more such systems need to be studied to further the understanding of these binary systems and the temporal variation in the physical parameters of the surrounding medium from their effect on the non-thermal spectrum. Observations at GMRT frequencies which have minimal contribution from thermal emission can be used to obtain the nature of the non-thermal spectrum. Moreover with the availability of automated data analysis pipeline (Sirothia 2009) for analysing GMRT data, it is possible to quickly analyse data and obtain frequent sampling of data at different GMRT frequencies.

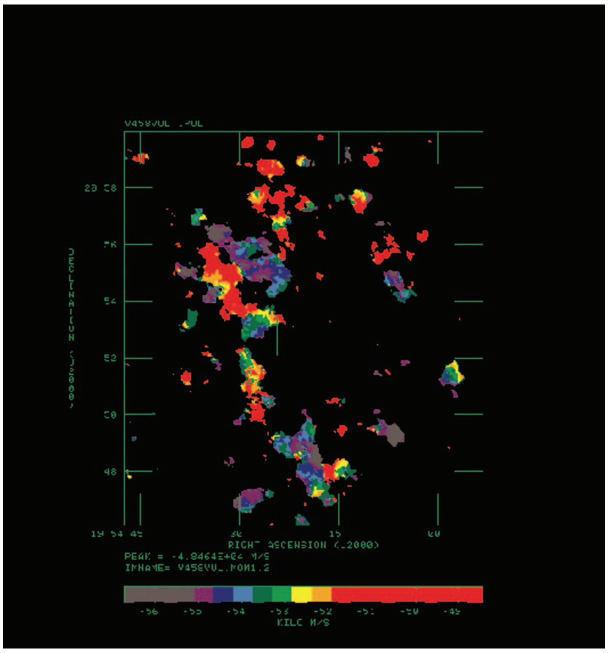

Figure 3. Kinematics (moment 1 map) of the HI gas detected around the nova V458 Vulpeculae. The optical position of the nova is marked in the figure with a cross. The velocity scale is given at the bottom. Notice the velocity structure in the broken shell immediately north-east of the optical position of the nova where the lower half shows velocities close to −51 km s^{-1} and upper half shows velocities close to −55 km s^{-1} indicating expansion. Also note the discrete clouds seen in a bigger asymmetric structure around V458 Vulpeculae with the northern half and southern half showing different velocities. However this latter result needs to be confirmed since GMRT is not sensitive to large scale structure beyond 7′ or so. Results published in Roy et al. 2012b. Figure courtesy: Nirupam Roy.

3.3 The classical nova: V458 Vulpeculae

An outburst in the classical nova V458 Vulpeculae was recorded in 2007 prompting intense monitoring in several wavebands with several telescopes around the world as was done in the case of RS Ophiuchi. This kind of quick coordinated observing has advanced our understanding of these enigmatic binary systems. The outburst has had no reported radio detection. Narrow band GMRT observations were conducted in 2009 to search for non-thermal continuum emission at 1.4 GHz and for HI 21cm emission from the planetary nebula detected in Hα by Wesson et al. (2008).

No radio continuum emission at 1.4 GHz was detected down to a 3σ limit of 1 mJy. However, discrete HI clouds were detected (Fig. 3) in emission near the nova with radial velocities ∼ −53 km s^{-1} and narrow line widths ∼ 5 km s^{-1}. These results are reported in Roy et al. (2012b). Considering that the radial velocity of the nova is −60 km s^{-1} (Wesson et al. 2008) and the direction is in the first Galactic quadrant where radial velocities are positive within the solar circle, this indicates that the Hɪ clouds and the nova are part of the same cloud complex which has peculiar velocities or lies beyond the solar circle. No Hɪ emission at positive velocities is visible in the maps since that emission is smooth and distributed over large angular scales. An expanding broken shell is detected to the north-east of the nova (Fig. 3). Moreover, position angle of the major axis of this shell appears to be similar to that noted for the Hα planetary nebula (Wesson et al. 2008). Based on the observed expansion and location, Roy et al. (2012b) suggest that the shell is associated with the nova V458 Vulpeculae. They suggest that the mass loss, which has subsequently swept up interstellar Hɪ, started in the asymptotic giant branch (AGB) phase of the white dwarf. Several stars in their AGB phase of evolution have Hɪ associated with the mass loss (e.g. Gérard & Le Bertre 2006) as do planetary nebulae.

The detected lines are narrow implying that the temperature of the gas is less than 500 K. At a distance of 13 kpc (Wesson et al. 2008), the mass of the Hɪ nebula is estimated to be ~ 25 $M_\odot$ (Roy et al. 2012b) which is too massive for a typical cold neutral medium cloud. At a distance of 13 kpc, V458 Vul would be about 800 pc below the Galactic plane, a bulge nova. Lockman (2002) found that a significant fraction of the rotating Hɪ gas detected in the halo is organised in the form of discrete clouds. Lockman (2002) found that the lines are fairly narrow (5.4 to 26.3 km s^{-1}) and mass of the clouds are in the range 12 – 290 $M_\odot$. The properties of the gas cloud detected near V458 Vulpeculae appears similar to this. Thus if the nova is located at such a large distance then it is likely to be in a halo Hɪ cloud. A larger Hɪ shell around the nova is also detected as shown in Fig. 3. However this needs confirmation with a telescope which is sensitive to larger angular scales than GMRT at 1.4 GHz.

Thus the main results of the GMRT study on V458 Vulpeculae presented by Roy et al. (2012b) can be summarised to be: (1) A large expanding broken Hɪ shell is detected in the vicinity of V458 Vulpeculae with both showing similar local standard of rest velocities indicating proximity. (2) The shell is associated with V458 Vulpeculae and a result of the interaction of the nova system with the interstellar medium in the AGB phase of evolution of the white dwarf. (3) The Hɪ mass in the broken shell is estimated to be $\approx 25 M_\odot$ for a distance of 13 kpc. (4) The nova shows a large proper motion as recorded in the NOMAD catalogue which if believed suggests that the nova has a large space velocity (~ 1200 km s^{-1}) if at 13 kpc else that the nova is closer. (5) A larger asymmetric Hɪ structure around the nova is detected which might also be associated with V458 Vulpeculae but requires confirmatory observations with a telescope sensitive to such large angular scales. (6) It was possible to detect this system in Hɪ with GMRT since it has a peculiar velocity, shows structure and high spectral resolution of the observations.

3.4 The Helium nova - V445 Puppis

A nova eruption similar to a classical nova was recorded in V445 Puppis on 28 November 2000. From their study of this nova, Ashok & Banerjee (2003) suggested that it was the first observed case of a Helium nova since it showed an absence of hydrogen and overabundance of helium and carbon in its spectrum. Bipolar nebulosity due to dust was observed around V445 Puppis (Woudt

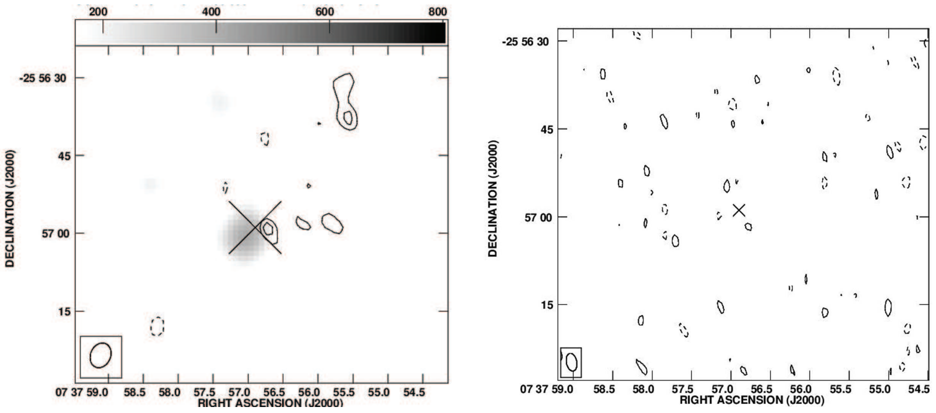

Figure 4. Radio images of the region around the nova V445 Puppis which had an outburst in 2009. The left image shows the radio contours at 1280 MHz from data obtained on 29 October 2009. The grey scale shows the 8 GHz image made from VLA archival data taken on 23 January 2007. The cross marks the optical position of the nova. The contours are plotted at -225, 225 and 300 μJy/beam. Notice the emission close to the optical position of the nova and skirting the 8 GHz emission. The right side panel shows the image made at 1400 MHz using GMRT data taken on 10 December 2009. The contours are plotted for -60, 60, 120 μJy/beam. No emission close to the nova or the emission detected to the north-west of the nova are visible in this image making it difficult to make any conclusive statement (Ashok, Kantharia, Banerjee).

et al. 2009). Interestingly radio emission at several frequencies between 1.4 and 43 GHz has been observed by Rupen et al. (2001a,b) and reported at http://www.aoc.nrao.edu/~mrupen/XRT/V445Pup/v445pup.shtml. The authors estimated a spectral index of -0.7 for the synchrotron emission. They also reported several flares in the light curve evolution, as seen in the plots available at the above mentioned website.

Following the discovery of the dense dust shell around the nova system (Woudt et al. 2009), it was clear that the nova was evolving in a dense medium thus increasing the probability of shock interaction. Moreover the nova remnant had been detected at 1.4 GHz and higher frequencies (Rupen et al. 2001a,b). Thus observations at GMRT were requested. Director's Discretionary Time was granted to observe the system in the 1280 MHz and 610 MHz bands in 2009. The nova was observed on 28 October 2009 in the 610 MHz band and on 29 October 2009 in the 1280 MHz band. The image at 610 MHz was noisy and no emission was detected. However the image at 1280 MHz had a rms noise of 75μJy (Fig. 4) detected faint emission close to the 8 GHz radio source. The 8 GHz image was made from the VLA archival data of January 2007. Since the image quality at 1280 MHz was excellent, we requested one more epoch of observing with GMRT to confirm this. Data at 1400 MHz were obtained on 10 December 2009. The image made from this data is shown in the right hand side panel in Fig. 4 - no emission was detected down to a 3σ limit of 60μJy on this day. Thus, the results by Ashok, Kantharia & Banerjee were perplexing.

A flux density of 20 mJy is detected near 1.4 GHz as seen at http://www.aoc.nrao.edu/ mrupen/XRT/V445Pup/v445pup.shtml#spec. At the estimated distance of 8.2 kpc this would correspond to a luminosity of 1.5×10^{14} W Hz^{-1}. This makes the system 10 times more radio bright compared to the RS Ophiuchi system.

This is an interesting nova system, ideal for studying at GMRT frequencies. The non-thermal radio emission seems to have been present at least till 2007.

4. Future nova observations at GMRT frequencies

Nine, of the total $\sim$ 33 novae that have been detected in the radio bands, have shown the presence of non-thermal emission in their radio spectrum. Out of these nine novae, four are classified as recurrent and the rest are classical novae. Thus, recurrent novae are excellent targets for observations at GMRT frequencies. These observations when done over a range of epochs starting with frequent temporal sampling soon after the outburst, to infrequent sampling a few years after the outburst, with the former investigating the shock interaction with the CMB and the latter with the interstellar medium (including mass loss from an earlier evolutionary stage) would be useful. In the case of RS Ophiuchi, hard X-ray emission was detected soon after the outburst and dominated the total X-ray flux till about day 6 (Bode et al. 2006). The authors explained this hard X-ray as thermal emission from the shocked gas with temperatures $10^7 - 10^8$K. Radio emission at 6 GHz was detected starting from day 4 and the multifrequency data suggested that the emission was a combination of thermal and non-thermal emission (Eyres et al. 2009). Strong radio emission (50 mJy) at 1280 MHz was detected on day 11 by GMRT (Kantharia et al. 2007). The strength of the radio source indicated that the emission had been visible before day 11. The radio emission from the shock interaction was imaged starting day 13 (O'Brien et al. 2006) which showed that emission was non-thermal, and expanding asymmetrically. Since both hard X-rays and non-thermal radio emission depend on shocks imparting energy to the circumbinary material; a correlation in the temporal evolution can be expected, even though the emission mechanisms are different. The subsequent GMRT observations at 240 MHz, 325 MHz and 610 MHz detected the nova with peak emission observed on days 45, 53 and 29 respectively. Our first observation and detection at 610 MHz was on day 20 when we detected a flux density of 48 mJy; again this strong radio source was observable earlier if GMRT observations had been obtained. Thus, instant followup observations of a reported recurrent nova are desirable at GMRT frequencies and justifiable since the detection rate is more than 40%. The science case is equally strong as we outline below.

Data at other wavebands and distance to the nova should be used to gauge the detectability of radio emission at GMRT frequencies for a set of physical conditions. For example, the peak luminosity in the 610 MHz band for RS Ophiuchi was $\sim 15 \times 10^{12}$ W Hz^{-1} for a distance of 1.6 kpc to the nova. Using a typical 3σ detection limit of 1 mJy at 610 MHz; GMRT should be able to detect a nova with similar non-thermal radio power to a distance of about 10 kpc. A range in the radio power from nova systems have been probed as listed in Table 2. There cannot be a typical radio power for a nova system since it is a function of the outburst energy which is in the range $10^{38} - 10^{43}$ ergs, ambient medium densities, particle acceleration and magnetic field strengths. Thus, no radio emission at GMRT frequencies is expected from an energetic nova unless it is evolving in a dense environment. Hence a smaller fraction of classical novae (where the secondary companion is generally a main sequence star) are likely detectable at GMRT frequencies, especially following a nova outburst, as compared to the recurrent class of novae (where the secondary companion is a large evolved giant star).

The mass of the white dwarf in a recurrent nova system is estimated to be close to the Chandrasekhar mass limit and is believed to be one of the reasons for the recurrent outbursts. Thus recurrent novae are strong contenders as progenitor systems of type 1a supernovae. However intriguingly, no radio emission has ever been detected from Type 1a supernovae down to a peak radio luminosity of 1.2×10^{25} ergs^{-1}Hz^{-1} (Hancock et al. 2011). Since non-thermal emission is observed from recurrent novae indicating sufficient mass loss from the secondary and particle acceleration; the aforementioned remains a mystery.

In this context, it would be invaluable to monitor all the outbursts of recurrent novae as soon as possible at GMRT frequencies and derive an evolutionary sequence for the radio emission at GMRT frequencies with outbursts. This does require several novae outbursts within a reasonable timeframe. Monitoring of multiple outbursts in RS Ophiuchi and U Scorpii has demonstrated that this is feasible. The outbursts in several novae can also be used to understand temporal evolution of non-thermal radio emission in these systems. Such observations would provide a diagnostic to the evolution of the density of the circumbinary material and mass loss rate of the secondary. For example, in the case of RS Ophiuchi; no radio emission was detected at 325 MHz on day 56 (Spoelstra et al. 1987) down to a 3σ limit of 12 mJy whereas 57 mJy was detected on day 53 following the 2006 outburst (Kantharia et al. 2007). The difference was explained as being due to the modified densities in the circumbinary material with those in 2006 being lower than in 1985 by 30% (Kantharia et al. 2007). Thus the change in the densities of foreground thermal CBM could be inferred from the observations of two outbursts of the same recurrent nova at GMRT frequencies. Such concerted studies might be able to give clues to the lack of detectable radio emission from type 1a supernova or/and subsequent progression of a recurrent nova to a type 1a supernova. Note that no non-thermal emission has been detected from about 60% of the recurrent nova population. These could be due to (1) lack of observations at the appropriate epochs (2) distance to the nova (3) physical conditions making particle acceleration ineffective (4) low magnetic fields. Intensive monitoring of recurrent nova at GMRT frequencies immediately following an outburst would break some of the aforementioned degeneracy. Having said the above, one has to remember that till date only 10 nova systems have been classified as recurrent. This list should be augmented by including the novae, from the classification based on the evolutionary type of the secondary (Darnley et al. 2012). The authors suggest a few possible novae which likely have a red giant/sub-giant companion. All the novae which host an evolved giant star as the companion are promising targets for followup study at GMRT frequencies and hence this classification is more relevant for planning observations at GMRT frequencies.

Till date around 33 out of the total of about 400 novae known have been detected in radio with only five classical novae showing the presence of non-thermal emission in their spectra. This is only $\sim 1\%$ of the total number of known classical novae. This could again be a result of the points listed above for recurrent novae. An additional reason for the low detection rate of non-thermal radio emission from classical nova outbursts could also be the paucity of dense circumbinary material which could give rise to synchrotron emission. However these systems should also be investigated with GMRT whenever possible. And we again mention that the novae which are evolving in a dense environment should be vigorously targeted with GMRT.

Nova remnants such as the GK Persei can also be studied at GMRT frequencies long after the emission associated with the shocked CMB has faded. A few relatively long-lived remnants have been observed at radio frequencies (see O'Brien& Bode (2008) for details). While the evolution of such systems is qualitatively similar to supernova remnants; nova remnants are several orders of magnitude lower in energy. Thus such systems are likely to be detected if located in the solar vicinity. For example, the remnant-integrated emission from GK Persei at 610 MHz was recorded to be 21.8 mJy i.e. a luminosity of 6.5×10^{11} W Hz^{-1} for a distance of 500 pc. For a detection limit of 1 mJy, this would be detectable upto a distance of 2.3 kpc.

The spectral line of HI at 21cm has been used to probe the atomic gas around a couple of novae using GMRT. The results have been interesting and is another interesting field which can be pursued at GMRT frequencies. The HI could be from the planetary nebula leftover from the mass loss episodes in the AGB phase of the white dwarf or or it could be the swept up interstellar medium. GMRT has detected the planetary nebula around GK Persei and the expanding HI shell associated with the nova V458 Vulpeculae. Such observations are possible with GMRT and can advance our understanding of the mass loss in the system and its interaction with the ambient interstellar clouds in addition to studying the atomic HI in planetary nebulae. In both the above cases, the detections were possible either because of the proximity of the nova system or the discrete nature of clouds and peculiar velocity of the nova system and the HI cloud. GMRT as an interferometer is well-suited for these studies since it resolves the smooth component of the HI emission.

Thus, in summary, novae are intriguing objects and progress is being made to understand the non-thermal emission from these systems with excellent results given by MERLIN, VLBI, JVLA, GMRT. GMRT with its frequency coverage and angular resolutions is best suited to explore the following particular science goals and make important contributions therein: (1) monitoring non-thermal radio continuum recurrent novae, especially successive recurrent nova outbursts to study the evolution of the radio emission. This could possibly give clues to the lack of radio emission from a type 1a supernova if recurrent novae are progenitor candidates. (2) HI observations of the atomic gas around novae systems to study the planetary nebulae and interaction of mass loss, from an earlier evolutionary epoch, with the ISM. These studies can be followed up by a search for a nova remnant if the nova is found to be embedded in a dense cloud.

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