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An H I shell-like structure associated with nova V458 Vulpeculae?

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ABSTRACT

We report the radio detection of a shell-like H I structure in proximity to, and probably associated with, the nova V458 Vul. High spectral resolution observation with the Giant Metrewave Radio Telescope has made it possible to study the detailed kinematics of this broken and expanding shell. Unlike the diffuse Galactic H I emission, this is a single-velocity component emission with significant clumping at ∼0.5 arcmin scales. The observed narrow-line width of ∼5 km s^{-1} suggests that the shell consists of mostly cold gas. Assuming a distance of 13 kpc to the system, as quoted in the literature, the estimated H I mass of the nebula is about 25 M$_{\odot}$. However, there are some indications that the system is closer than 13 kpc. If there is a physical association of the H I structure and the nova system, the asymmetric morphology and the off-centred stellar system indicate past strong interaction of the mass loss in the asymptotic giant branch phase with the surrounding interstellar medium. So far, this is the second example, after GK Per, of a large H I structure associated with a classical nova.

Key words: stars: individual: V458 Vul – novae, cataclysmic variables – ISM: general – radio lines: ISM.

1 INTRODUCTION

Classical novae (CNe) are interacting binaries, with orbital periods of hours to around one day. A white dwarf (WD) accretes gas from a main-sequence companion, and the build-up leads to a thermonuclear runaway (TNR) in the surface material. This generates a fireball, leading to the visual brightening that allows us to detect these events. This is accompanied by the ejection of around 10^{-4} M$_{\odot}$ of material at velocities of 200–5000 km s^{-1} (see e.g. Warner 2008, for a recent review). These episodic stellar explosions are commonly detected at optical wavelengths and provide valuable understanding of the nuclear burning and accretion phenomena.

Most of the CNe follow a maximum-magnitude-rate-of-decline (MMRD) relationship, where the time to decay by 2 or 3 mag from optical maximum (t_2, t_3, respectively) is a reasonable indicator of the absolute magnitude (e.g. Downes & Duerbeck 2000). As well as providing a distance estimate, this indicates that the underlying mechanism is fairly uniform across different examples. The rate of decline also defines a speed class – from very fast to slow – and it is evident that the fastest novae are also the most energetic (being intrinsically brightest and having the fastest ejecta). This suggests a link between the development of the ejecta, the progress of the explosion and the energetics (including any dependence on dredged up material) of the TNR (e.g. Shara, Prialnik & Shaviv 1980).

V458 Vul was identified as a CN on 2007 August 8 (IAU Circular 8861) with magnitude 9.5 (Nakano et al. 2007). After reaching a maximum brightness of $V = 8.1$, the optical light curve showed unusual multiple peaks in the following weeks. If these additional peaks are ignored, it seems likely that for V458 Vul $t_3 \sim 21$ d, making this a fast nova. The MMRD relationship gives a distance of 13.5, 11.6 and 10.0 kpc to V458 Vul using t_2, t_3 and t_{15}, respectively (Downes & Duerbeck 2000; Wesson et al. 2008). Henden & Munari (2007) identified the star USNO-B1.0 1108 − 0460444 as the 'viable progenitor for the nova' based on its colour and proximity to the nova position (within 0.6 arcsec; Nakano et al. 2007). Within 5 arcsec of the nova position, there is no other source in the USNO catalogue (completeness down to $V = 21$). Earlier spectra indicated V458 Vul to be an Fe II type nova, whilst later spectra were consistent with an He/N type. This suggests that, in the spectral classification scheme of Williams, Phillips & Hamuy (1994), V458 Vul is a hybrid nova (Poggiani 2008). X-ray observations initially showed emission consistent with an expanding shock (Tsujimoto

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et al. 2009), before a soft component, reminiscent of RS Oph, came to dominate (Drake et al. 2008) with a 12 h oscillation becoming apparent, as this emission declined over 2008 (*Swift* nova consortium). In RS Oph this was associated with the unveiling of continued hydrogen burning on the WD surface (Osborne et al. 2011). Follow-up spectroscopy has established the orbital period of the binary system to be 98 min (Rodríguez-Gil et al. 2010).

The field containing V458 Vul was observed both before and after the nova event, as part of the IPHAS Galactic Plane Survey. Wesson et al. (2008) identified a planetary nebula in the Hα images, with a semimajor axis of 13.5 arcsec, with a position angle of $\sim 30°$, centred to within 1 arcsec on the nova seen in the later IPHAS images. Further follow-up imaging and spectroscopic observations of the nebula showed an inner nebular knot, brightened by the flash ionization. This nebula, with an ionized mass of 0.2 $M_{\odot}$, is suggested to be a 14000 yr old planetary nebula originating from the common-envelope phase of the binary system (Wesson et al. 2008).

In this Letter, we report results of our radio observation at 1420 MHz of the H I emission towards V458 Vul. This observation reveals a shell-like H I structure close to, and probably associated with, the nova. The observation, analysis procedure and the results are presented in Section 2. Section 3 contains discussion on possible implications of these results, and our conclusions are presented in Section 4.

2 OBSERVATION, ANALYSIS AND RESULTS

V458 Vul was observed with the Giant Metrewave Radio Telescope (GMRT) with the aim of detecting any associated H I 21 cm emission, and to search for possible radio continuum from the nova shell. Bandpass calibration for this observation was carried out with the flux and phase calibrators, but with frequency switching at the first local oscillator, using a frequency throw of ± 5 MHz. For details of GMRT observations using frequency switching, see Roy & Kanekar (2007). Standard flux calibrators 3C286 and 3C48 (at start and end of the observation, respectively) were observed for ~ 30 min (10 min for each of the three frequency settings). A phase calibrator, 1924+334, was also observed in between the target source scans with each of the three frequency settings. A summary of the observations is given in Table 1.

All data were analysed in the Astronomical Image Processing System (AIPS) of the National Radio Astronomy Observatory (NRAO), using standard procedures. Some of the data were flagged to remove interference and instrumental misbehaviour. After removing bad data, the standard calibration procedure was followed to obtain the antenna-based complex gains. The bandpass solution was derived from the ± 5 MHz frequency setting scans of the calibrators, and the calibration was applied to the central frequency target source scans using interpolation between bandpass solutions. Next, the line-free channels were used to make a continuum image of the field. No radio continuum was detected at the nova position with a 3σ limit of 1 mJy.

The continuum-subtracted residual data were imaged with CLEANING in all channels. To recover weak and diffuse emission structures, data from longer baselines were given a lower weight while making images. The restoring beam of the final image cube was 30×30 arcsec^2 and the rms noise per channel was ~ 1.3 mJy beam^{-1}. From this image cube, the moment maps were made using the channels with significant emission above 3σ noise level. Finally, this was converted to H I column density units assuming optically thin emission (Kulkarni & Heiles 1988). As shown in Fig. 1, we have detected discrete H I clouds in the vicinity of V458 Vul with velocities ~ -55 km s^{-1}. If the gas velocity is due to Galactic rotation only, the kinematic distance of the structure is 13.5–14.5 kpc. A broken clumpy shell-like H I structure north-east of the nova position is clearly visible in this image. No such clumpiness at similar scales was seen in the H I maps at the positive velocities, indicating that the H I emission component is smoothly distributed over large angular scales, which is typical of the hot atomic gas detected in the H I 21 cm emission line in our Galaxy. The details of column density and velocity field of the broken H I shell are shown in Figs 2 and 3(a), respectively. Fig. 3(b) shows the H I emission in different channels for the velocity range of -46.8 to -60.0 km s^{-1}, covering the spectral region of interest. The central channels show a line-of-sight velocity difference of ~ 3.5 km s^{-1} between the south-east and north-west rim.

The integrated spectrum of the H I shell is shown in Fig. 3(c). The blue line is the best-fitting Gaussian profile with a full width at half-maximum (FWHM) of only 4.9 ± 0.3 km s^{-1}. If there was no non-thermal broadening, this would correspond to a temperature of ~ 525 K. However, as noted above, at least ~ 3.5 km s^{-1} is due to

Table 1. Summary of the GMRT observation of V458 Vul.

Source position (J2000)	RA 19^{h}54^{m}24^s.61 Dec. +20°52′52″.6
GMRT pointing centre (J2000)	RA 19^{h}54^{m}24^s.3 Dec. +20°52′47″.0
Date of obs.	2009 June 11–12
Bandwidth	2.0 MHz, $\sim$420 km s^{-1}
No. of channels	256
Spectral resolution	$\sim$1.6 km s^{-1}
Calibrators	3C48, 3C286, 1924+334
Observation time	Total: $\sim$10 h, On source: $\sim$4 h

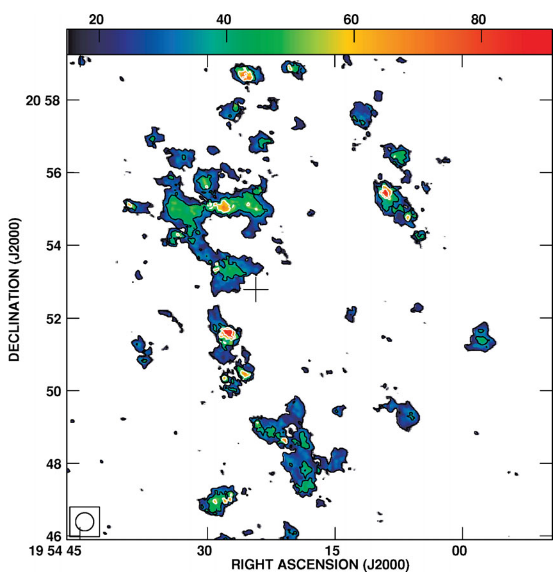

Figure 1. Integrated H I column density map of the field showing large-scale H I emission for the velocity range of $V_{LSR} \approx -60$ to -50 km s^{-1}. The synthesized beam size is 30×30 arcsec^2, and the colour scale is in mJy km s^{-1} beam^{-1}. The contour levels are for H I column density of (1, 2, 3, 4, 5) times 2.5×10^{19} cm^{-2}. The lowest contour corresponds to a 3σ cut-off based on rms noise per channel (see Section 2 for details). The optical position of V458 Vul is marked with a +. Note the broken shell-like structure north-east of the nova position.

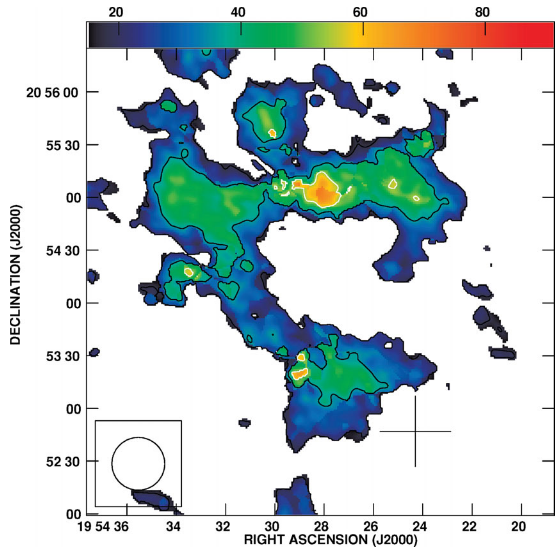

Figure 2. Zoom-in from Fig. 1, showing the H I column density map of the broken shell. Contour levels and grey-scales are the same as in Fig. 1.

the internal dynamics of the H I structure. There may also be some contribution from turbulence. So the actual kinetic temperature is likely to be considerably lower. We also used the line profile to estimate an H I mass of $(25.0 \pm 2.3) \times d_{13}^2\,\mathrm{M}_\odot$, where d_{13} is the distance in units of 13 kpc.

The H I emission towards V458 Vul (in the first Galactic quadrant) detected near $V_{\rm LSR} = -53\,\mathrm{km\,s^{-1}}$ is a single narrow emission component, while rest of the H I towards V458 Vul (and also towards the nearby phase calibrator 1924+334) at positive velocities has multiple components spread over $>50\,\mathrm{km\,s^{-1}}$. The H I emission near $-53\,\mathrm{km\,s^{-1}}$ shows clumping at ∼0.5 arcmin scales. In contrast, the H I emission detected at positive velocities is more widespread and of relatively uniform brightness over the GMRT primary beam with no significant clumping below ∼10 arcmin. The narrow H I line width of the shell suggests that the gas is cold. However, the estimated size and mass (∼$7.6 \times d_{13}$ pc and $25 \times d_{13}^2\,\mathrm{M}_\odot$, respectively) are larger than the typical size and mass scales (1−2 pc and 2−5 $\mathrm{M}_\odot$, respectively) of the Galactic cold neutral medium. These characteristics indicate a possible peculiar origin (e.g. association with V458 Vul, shaped by an early phase of mass loss and interaction) of this shell.

3 DISCUSSION

In this Letter, we report the discovery of a large asymmetric shell-like structure in H I to the north-east of V458 Vul. At the maximum likely distance of 13 kpc, the average projected linear diameter of the H I structure is about 7.6 pc. For comparison, GK Per has a planetary nebula of size 6 pc with associated H I structure (Seaquist et al. 1989; Anupama & Kantharia 2005). Moreover, there have been reports of planetary nebulae observed in dust emission at infrared wavelengths which are several parsecs in size (Weinberger & Aryal 2004). So, a size of a few parsecs is not inconsistent with our interpretation of this structure as being associated with V458 Vul. V458 Vul is thus the second CN found to be associated with a large H I structure.

If the H I structure and the nova have a physical association, we may interpret this shell as a remnant of the interaction with the surrounding interstellar medium (ISM) in the asymptotic giant branch (AGB) phase of evolution of the WD. The H I structure, which appears to be ram pressure swept gas, has a size of about $2.4 \times 1.8\,\mathrm{arcmin}^2$ at a position angle of ∼30° and a systemic velocity of $-53.2\,\mathrm{km\,s^{-1}}$. Interestingly, the position angle is very close to the orientation of the planetary nebula detected by Wesson et al. (2008), though the angular size of the planetary nebula is much smaller (∼27 arcsec). This, we believe, supports a common origin to this axis. It might indicate the ISM density structure or the axis of mass loss in the binary system.

3.1 The asymmetric H I shell: evolution in the AGB phase

The asymmetric nature of the structure and the off-centred stellar system may be attributed to a number of causes including the effect of the interaction of the stellar wind with the ISM, the effect of the binary stellar system and magnetic field effects (e.g. Kwok 1982; Soker 1989; Chevalier & Luo 1994; Dwarkadas, Chevalier & Blondin 1996; Blackman et al. 2001; Soker & Rappaport 2001).

Simulations by Borkowski, Sarazin & Soker (1990), Soker, Borkowski & Sarazin (1991) and more recently by Wareing et al. (2007b) have examined the interaction of ambient ISM with systems with continuous or episodic mass loss. Though these are mainly in the context of planetary nebulae, they can explain several of the observed features in this asymmetric H I structure. Wareing et al. (2007b), in particular, show that, in about 3×10^4 yr into the post-AGB evolution, the central stellar system is not at the centre of planetary nebula and the nebula is highly asymmetric with the brighter emission in the downstream regions. For a

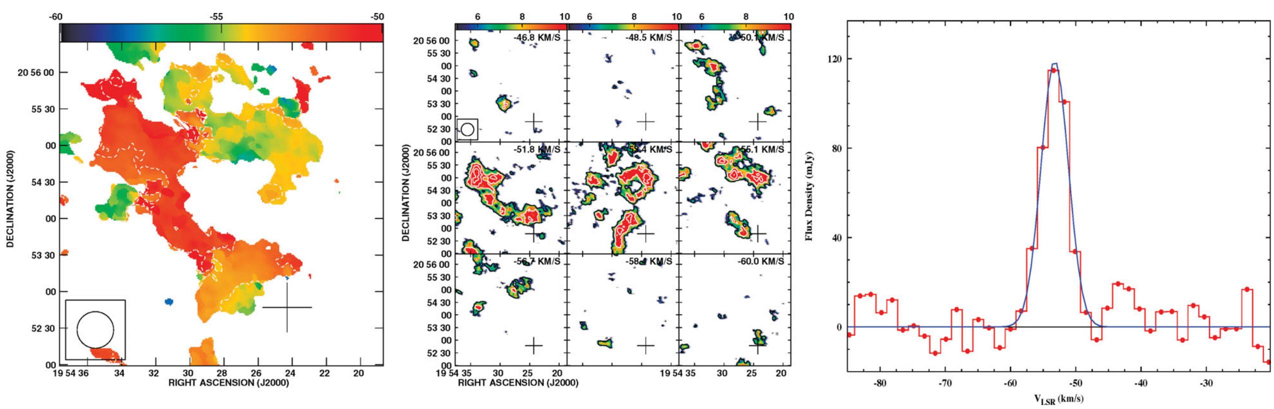

Figure 3. (a) H I velocity field of the region shown in Fig. 2. (b) H I emission near V458 Vul in different spectral channels. The LSR velocities for each channel are listed in the top right-hand corner of the respective panels. (c) Integrated H I emission spectrum of the broken shell. The blue line is the best-fitting Gaussian profile with FWHM of $4.9\,\mathrm{km\,s^{-1}}$.

density of $2\,\mathrm{cm^{-3}}$ of the surrounding ISM, Wareing et al. (2007b) find that atomic densities up to 50–100 $\mathrm{cm^{-3}}$ can be present in the ram pressure stripped flow in the downstream region. This is similar to and consistent with our estimated density of about $10\,\mathrm{cm^{-3}}$ in the H I structure for a distance of 13 kpc.

Several AGB stars have been observed and detected in H I emission (Gérard & Le Bettre 2006, 2007) and many of these stars show a circumstellar envelope of size ∼1 pc. More recently, Matthews et al. (2011) report the detection of a circumstellar wake and a compact high-velocity cloud near the AGB star X Herculis. Matthews et al. (2008) reported the detection of an H I tail coincident with part of the 4 pc long tail in the far-ultraviolet trailing the AGB star o Ceti. Martin et al. (2007) suggest that the long tail in this case is a result of the large space velocity ($\sim 130\,\mathrm{km\,s^{-1}}$) of the Mira variable (which is a binary system) and the interaction between the ISM and the stellar wind. Wareing et al. (2007a) concluded, from their simulations of the system, that the long tail is a result of mass loss from the AGB star over 4.5×10^5 yr.

Thus, we infer that (i) large H I structures and tails associated with stellar systems in the AGB or post-AGB phase are fairly common, and (ii) the observed asymmetry of the H I structure associated with V458 Vul may be due to the motion of the nova system with respect to the ambient ISM (see also Bode, O'Brien & Simpson 2004, for evidence of this in GK Per). Unfortunately, such structures are difficult to detect due to the presence of Galactic emission kinematically corrupting the circumstellar emission and the inherently weak signal which limits detections only to nearby systems with peculiar velocities.

3.2 Distance, age and kinematics

Distance estimates to novae have always been difficult to obtain and V458 Vul is no exception. From the different estimates in literature, it is clear that the distance estimate to V458 Vul is uncertain by at least a factor of 2. Wesson et al. (2008) estimate a range of 10–13.5 kpc from MMRD relation. Their estimations of the distance, based both on the light travel time argument and on the assumption that mean radial velocity of $V_{\mathrm{LSR}} = -60.6\,\mathrm{km\,s^{-1}}$ is due to Galactic rotation, are also consistent with a distance of ∼13 kpc. Poggiani (2008) estimate the distance to be in the range of 6.7–10.3 kpc using several methods, some of them similar to Wesson et al. (2008). Recently, Rajabi et al. (2012) have reported a distance of 9.9–11.4 kpc by modelling the expansion of ejecta based on optical interferometric observation. On the other hand, Gordon (2011) estimates the distance to be 5–6.5 kpc using the method of light echoes (although light echo modelling by Hounsell 2012 gives $d \sim 13$ kpc). Note that the line-of-sight velocity may be anomalous (like the high-velocity clouds), and the actual distance may be very different from the kinematic distance. Also, with no reported observation before August 8, both the maximum magnitude and the rate of decline are highly uncertain in this case. Moreover, multiple peaks in the declining part of the optical light curve make defining t_2 and t_3, and hence using MMRD relationship, non-trivial in this case. It is also important to note here that, even with exact determination of peak apparent magnitude and rate of decline, the intrinsic scatter of the MMRD relation (e.g. della Valle & Livio 1995; Downes & Duerbeck 2000) and the uncertainty of extinction can result in a factor of ∼2 uncertainty in the derived distance.

Obtaining a reliable distance estimate to the nova system is important in determining the physical parameters of the H I structure. In Table 2, the derived parameters for the system are presented assuming different distances to the nova. The columns in Table 2 are (i) assumed distance, (ii) size and (iii) mass of the H I shell, (iv) dynamical age of the shell for an average radius of 60 arcsec assuming an expansion velocity of $10\,\mathrm{km\,s^{-1}}$, (v) proper motion corresponding to the observed separation of V458 Vul from the centre of the H I shell, and (vi) tangential velocity corresponding to a proper motion of $20\,\mathrm{mas\,yr^{-1}}$ (see more on this below). Note that even if the line width is $\sim 5\,\mathrm{km\,s^{-1}}$, as we do not know the inclination, we have used a typical value of $10\,\mathrm{km\,s^{-1}}$ for expansion velocity. If the expansion velocity on the sky plane is the same as the line-of-sight expansion velocity, the age will be about factor of 2 higher. Interestingly, in spite of the significant spatial displacement between the H I structure and the planetary nebula, and the difference in their estimated ages, their radial velocities are reasonably close ($V_{\mathrm{LSR}} = -53.2$ and $-60.6\,\mathrm{km\,s^{-1}}$, respectively).

Table 2. Derived physical parameters of the H I structure for different assumed distances. The columns in the table are listed as follows: (1) distance to the nova (D); (2) size of the H I shell ($d_{\mathrm{H\,I}}$); (3) H I mass; (4) estimated dynamical age ($t_{\mathrm{dynamical}}$); (5) proper motion (μ) corresponding to the observed separation of V458 Vul from the centre of the H I shell; and (6) tangential velocity (v_{t}) corresponding to a proper motion of $20\,\mathrm{mas\,yr^{-1}}$. See Section 3.2 for details.

D (kpc)	$d_{\mathrm{H\,I}}$ (pc)	$M_{\mathrm{H\,I}}$ ($\mathrm{M_{\odot}}$)	$t_{\mathrm{dynamical}}$ (yr)	μ ($\mathrm{mas\,yr^{-1}}$)	v_{t} ($\mathrm{km\,s^{-1}}$)
13.0	7.6	25.0	3.7×10^5	0.27	1200
6.5	3.8	6.3	1.8×10^5	0.56	600
5.0	3.0	3.7	1.4×10^5	0.71	474
1.0	0.6	0.15	2.8×10^4	3.57	95

The star USNO-B1.0 1108 − 0460444 has been identified as the progenitor of V458 Vul by Henden & Munari (2007). The proper motion of the corresponding star listed by NOMAD[1] is about $-12 \pm 5\,\mathrm{mas\,yr^{-1}}$ in right ascension and $16 \pm 2\,\mathrm{mas\,yr^{-1}}$ in declination (with the highest value of the probability estimator assigned for the likelihood that the quoted proper motion is correct). This is roughly $20 \pm 3.5\,\mathrm{mas\,yr^{-1}}$ in the north-west direction. For a distance of 13 kpc, the proper motion translates to an unreasonably large value of tangential velocity of 260 ± 44 au per year, i.e. $1200 \pm 200\,\mathrm{km\,s^{-1}}$ (see Table 2). On the other hand, the required velocity, to displace the nova by the observed separation of ∼100 arcsec from the centre of the H I shell over this dynamical time-scale, is only $\sim 17\,\mathrm{km\,s^{-1}}$ or $0.27\,\mathrm{mas\,yr^{-1}}$ at 13 kpc (see Table 2). This is the vector sum of the proper motion of the star and the ejecta (which may be misaligned; Gérard, Le Bettre & Libert 2011). So, the proper motion of V458 Vul is expected to be smaller than this. Also, V458 Vul is centred to within 1 arcsec of the 14 000 yr old planetary nebula (Wesson et al. 2008), implying proper motion smaller than $0.07\,\mathrm{mas\,yr^{-1}}$. It is more likely that the NOMAD proper motion is spurious for such a faint object (e.g. due to issues with the older plates used to derive proper motion).

We also examined the possibility that USNO-B1.0 1108 − 0460444 is *not* the progenitor of V458 Vul. At a distance of ∼13 kpc, such a progenitor must be fainter than $V = 21$ ($M_V > 3.5$ for $A_V = 1.95$). Taking a conservative lower limit of $M_V = 10.5$, and using a typical stellar luminosity function (Kroupa 2002), the average number density of stars with $3.5 < M_V < 10.5$ is $\sim 2.5 \times 10^{-2}\,\mathrm{pc^{-3}}$. Considering the position uncertainty to be ∼0.6 arcsec, the volume, defined by a circle of 0.6 arcsec radius (on the plane of the sky

[1] The Naval Observatory Merged Astrometric Data set available online at http://www.nofs.navy.mil/nomad/ (Zacharias et al. 2004).

centred at the nova position) and a radial distance of 13 ± 2 kpc (2 kpc centred at a distance of 13 kpc), is about 9 pc^3. Within this volume, the average expected number of progenitor stars with the right M_V is about 0.22 (0.62 for 1 arcsec radius). The associated Poisson distribution probabilities are 0.18 and 0.33 for 0.6 and 1 arcsec, respectively. Clearly, the possibility of an alternative nova progenitor at a distance of ∼13 kpc is small.

If the H I structure has a physical association with the nova, as implied by various pieces of evidence above, then an indirect argument in favour of a smaller distance to the nova is from the estimated mass of the H I shell. At a distance of 13 kpc, the enclosed H I mass is $\sim 25\,M_\odot$ which is too large to be explained as swept-up mass. If the distance is $\lesssim$6.5 kpc, the H I mass may originate from a massive super-AGB progenitor. Such progenitors evolve to either neutron stars or massive O–Ne–Mg WDs (Herwig 2005). Interestingly, the massive ($>1\,M_\odot$) WD in V458 Vul is consistent with this scenario. If the NOMAD proper motion, as argued above, is incorrect, based on parameter values in Table 2, a distance $\lesssim$6.5 kpc seems plausible. It is important to constrain the proper motion of the faint nova progenitor, and if possible find tracers from the nova outburst which would give independent distance estimates, to cross check this suggestion of a smaller distance to V458 Vul.

3.3 Possible large-scale H I structure

The above discussion has been mainly restricted to the shell-like expanding structure north-east of V458 Vul. However, high-velocity H I has been seen over a much larger region around V458 Vul. There are discrete clouds scattered around the nova with the central few arcminutes being devoid of H I (see Fig. 1). One possibility is that there is another larger shell which traces the mass-loss history at a still earlier evolutionary epoch of the nova binary system. This large shell (approximately 8 arcmin), with longer axis almost parallel to the smaller H I shell we discussed above, also has the nova off-centred. Moreover, this large shell seems to show weak evidence of expansion with the north/north-eastern parts moving at $-49\,km\,s^{-1}$ and the southern parts being close to $-55\,km\,s^{-1}$. However, this needs confirmatory observations especially since GMRT is expected to be missing flux on larger angular scales. No clear correlation is seen between the H I and the *IRAS*60 and 100 µm dust emission, though the H I shell appears to be located close to the edge of a dust cloud.

4 CONCLUDING REMARKS

From the above discussion, we conclude that we have detected an expanding shell of cold H I possibly associated with V458 Vul. If this is the case, it appears to be the remnant of the interaction of the nova system with the ISM in its AGB phase of evolution, as indicated by its slowing down and its peculiar morphology. However, at a distance of 13 kpc, the H I structure would have an unreasonably high mass of $25\,M_\odot$. There are some indications that the nova is closer than 13 kpc, and further independent constraints on the distance to the nova will be very useful.

Finally, it is relevant to mention that a large number of such systems might be distributed in the Galaxy. While we have detected the H I shell associated with V458 Vul, it is likely that there are several such structures which have not been detected in H I emission either because of the inadequate spectral resolution of such observations or because they are so far from the central stellar system that the association is not obvious. More observations targeting such systems may be useful to understand the interaction with the surrounding ISM and the mass-loss phase of the evolution of CNe progenitor system.

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