Simultaneous VLBA polarimetric observations of the $v=\{1,2\}$ $J=1-0$ and $v=1$, $J=2-1$ SiO maser emission toward VY CMa: maser morphology and pumping

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ABSTRACT

This paper presents a milliarcsecond-scale comparison of the polarised component-level $v=1$ $J=1-0$, $v=2$ $J=1-0$ and $v=1$ $J=2-1$ SiO maser emission toward the supergiant star VY CMa. These observations used the VLBA at $\lambda = 7$ mm and $\lambda = 3$ mm over two epochs. The goal is to use the relative characteristics and spatial distribution of the transitions in individual resolved maser components to provide observational constraints on SiO maser excitation and pumping models. We find that many $v=1$ $J=1-0$ and $v=2$ $J=1-0$ features overlap in the second observing epoch, at comparable sensitivity. The $v=2$ $J=1-0$ emission is primarily located within several $v=1$ $J=1-0$ regions, and has a high degree of morphological similarity in the northeastern envelope, supportive of local collisional pumping. We find significantly higher spatial overlap between $v=1$ $J=1-0$ and $J=2-1$ features than generally previously reported. However, the overlapping $v=1$ $J=2-1$ emission is usually weaker than predicted by hydrodynamical models, possibly due to low-density collisional pumping. The overall maser morphology contains several large-scale features that are persistent over multiple years and are likely associated with intrinsic physical circumstellar conditions. Our data cannot distinguish between competing near-circumstellar bulk kinematic models but do provide evidence for localized inhomogeneous mass-loss.

Key words: masers — stars: AGB and post-AGB — stars: individual: VY CMa

1 INTRODUCTION

SiO maser emission is commonly found in the atmospheres of late-type evolved stars (Habing 1996), and has been used as a probe of their near-circumstellar envelopes. High resolution VLBI images of the masers provide information about circumstellar envelope kinematics (Boboltz et al. 1995; Diamond & Kemball 2003; Zhang et al. 2012), and inform hydrodynamical models of the region (Humphreys et al. 1996, 2002; Gray et al. 2009).

However, the predominant pumping mechanism maintaining the circumstellar masers is still a subject of debate. Both radiative and collisional pumping mechanisms have been proposed (Kwan & Scoville 1974; Eiltzul 1981), and SiO maser hydrodynamical models have incorporated both, at varying levels of influence (Humphreys et al. 1996, 2002; Gray et al. 2009). The SiO maser pumping models make predictions about the extent of spatial overlap between maser emission from different SiO transitions, so observational tests are important in informing theoretical work on SiO maser pumping.

This paper reports two epochs of full-polarisation Very Large Baseline Array (VLBA) observations of SiO maser emission in the $v=\{1,2\}$ $J=1-0$ and $v=1$, $J=2-1$ transitions toward the highly luminous evolved star VY CMa. This source was chosen as the object of this study in spite of its complex circumstellar environment (Smith et al. 2001), but rather because it is such a strong SiO maser source, displaying emission from a wide range of SiO transitions (Cernicharo et al. 1993). Simultaneous observations of a range of SiO maser transitions in full polarisation at the component level provides stringent observational tests of

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SiO maser pumping models, and we present such an analysis here. The high SiO luminosity of VY CMa is also an important factor, given the sensitivity limitations of VLBI arrays at millimetre wavelengths.

Relevant predictions of the pumping models are discussed below, followed by a summary of existing comparative observations.

1.1 SiO maser pumping models

For both radiatively- and collisionally-pumped masers, the v=1 and v=2 J=1-0 transitions are inverted under different conditions (Lockett & Elitzur 1992; Bujarrabal 1994). However, while the basic theory of radiative pumping predicts almost no spatial overlap between v=1 and v=2 transitions, they are predicted to show a significant amount of overlap for collisional pumping (Lockett & Elitzur 1992). Considerable spatial overlap between the v=1 and v=2 J=1-0 emission therefore argues for a collisional pumping mechanism. In the collisional pumping model of Lockett & Elitzur (1992), the range of conditions under which the v=1 J=1-0 masing occurs is wider than that of the v=2 J=1-0 transition, with the v=2 line requiring higher-density conditions.

Alternatively, extensive overlap between the v=1 and v=2 J=1-0 emission may also be caused by a line overlap between the v2=0 1275 → v2=1 1166 H2O transition at 1219.10 cm⁻¹ and the adjacent v=1 J=0 → v=2 J=1 SiO transition at 1219.15 cm⁻¹ (Olofsson et al. 1981). This H2O line overlap mechanism was originally invoked to explain the anomalously low v=2 J=2-1 SiO maser emission generally found (Olofsson et al. 1981; Bujarrabal et al. 1996). Soria-Ruiz et al. (2004) investigated the effect of the proposed line overlap using the primarily radiative SiO maser excitation model of Bujarrabal et al. (1996). A key result of their work is that when the line overlap is included in radiative transfer calculations, the conditions for v=1 and v=2 J=1-0 masers to occur intersect considerably, but the conditions under which the v=1 J=1-0 and J=2-1 masers would occur simultaneously are, in contrast, far more limited.

SiO maser excitation models have been coupled to hydrodynamical models of the circumstellar environment, and used to create simulated images of SiO maser emission in circumstellar envelopes (Humphreys et al. 1996; Gray & Humphreys 2000; Humphreys et al. 2002; Gray et al. 2009). The models have had various successes, including predicting the existence of SiO maser emission from high angular momentum states above J=6 (Gray, Humphreys & Field 1993; Gray et al. 1994), and predicting the ring morphology of the maser emission (Humphreys et al. 1996). Although these models do include a radiative pumping component, the pumping mechanism is predicted to be and treated as predominantly collisional (Humphreys et al. 1996).

The hydrodynamical SiO maser models make a number of specific predictions about the relative location of SiO maser emission from the v=1 J=1-0, v=2 J=1-0 and v=1 J=2-1 transitions, and improve the predictive power of the multi-transition observational tests considered in this paper. The hydrodynamical model predictions are outlined in Humphreys et al. 1996, Humphreys et al. 2002, and Gray et al. 2009), and include the following specific predictions:

- The v=1 J=1-0 maser ring is thicker than that of the other two transitions, and maser emission occurs over a wider range of physical conditions (Gray & Humphreys 2000).
- The v=2 masers lie closer to the star than the v=1 masers (Gray & Humphreys 2000; Gray et al. 2009).
- The v=1 J=1-0 and J=2-1 lines often arise in shared components, in rings of similar radii, and the radial motions of the rings from these two lines are coupled (Gray & Humphreys 2000; Humphreys et al. 2003).
- Where v=1 J=2-1 and v=1 J=1-0 features overlap, the v=1 J=2-1 emission will be brighter (Humphreys et al. 2002).

Unlike the comparative v=1 and v=2 J=1-0 case, the v=1 J=1-0 and J=2-1 SiO maser emission is expected to be coincident from first principles under both radiative and collisional pumping schemes, as maser emission occurs along rotational ladders within a given vibrational state (Alcolea 2004). Lack of coincidence between v=1 J=1-0 and J=2-1 emission could be accounted for by a line overlap, as mentioned above, or by variable envelope conditions favouring one or the other transition in a particular location.

1.2 Previous comparative observations

Simultaneous imaging VLBI observations of the v=1 and v=2 J=1-0 masers have previously been performed towards numerous late-type evolved stars. The earliest maps, presented by Miyoshi et al. (1994) in total intensity, show overlap between maser features in these two lines. A subsequent higher-resolution total intensity and linear polarisation observation by Desmurs et al. (2000) showed a systematic offset between emission from the two transitions, which they put forward as evidence in support of radiative pumping models.

A number of subsequent observations at similar angular resolution to those of Desmurs et al. (2000) showed significant overlap between the v=1 and v=2 J=1-0 masers (Miyoshi 2003; Yi et al. 2005; Cotton et al. 2004, 2008). In the overlapping v=1 and v=2 features present in the Yi et al. (2005) maps, the v=2 emission tends to arise closer to the star than the v=1 emission, with an intermediate region of overlap.

More recent astrometrically-aligned maps of the v=1 and v=2 J=1-0 emission towards R Aquarii produced by the VERA array argue that the number of coincident maser spots in these two lines is actually small, but that v=1 and v=2 spots are clustered together and may appear coincident at lower resolution, or if absolute position information about the images is not available (Kamohara et al. 2010). This supports the Desmurs et al. (2000) result. Kamohara et al. (2010) find a number of spot clusters that have offsets of 1-2 mas between the v=1 and v=2 J=1-0 emission. However, the sensitivity of these VERA images is considerably lower than the VLBA images presented in several of the publications discussed above, so it is possible that weaker overlapping emission may not have been detected in the Kamohara et al. (2010) observations.

Simultaneous observations of the v=1 J=1-0 and v=1
J = 2-1 SiO masers are less common than those of v = 1 and v = 2 J = 1-0 SiO masers, due to the limited number of 86 GHz observing facilities and the technical challenges posed by observing at these frequencies. Most of the published simultaneous VLBI imaging of these lines do not display no clear evidence of overlapping maser emission. Desmurs et al. (2002), Soria-Ruiz et al. (2001, 2005, 2006, 2007). R Cassiopeiae is an exception, and displays overlapping v = 1 J = 1-0 and v = 1 J = 2-1 SiO maser features in a total-intensity VLBI map published by Phillips et al. (2003).

1.3 Outline of this work

We present a component-level comparison of the total intensity and linear polarisation properties of the SiO maser emission in the transitions v = 1,2 J = 1-0 and v = 1, J = 2-1 toward VY CMa, as well as an analysis of the overall morphology of the SiO maser emission toward this source.

We find that the v = 2, J = 1-0 emission is predominantly located within a subset of the v = 1, J = 1-0 emission regions overall, consistent both with the hydrodynamical models of Gray & Humphreys (2000) as well as a predominantly collisional pumping interpretation. In addition, we find a higher degree of overlap between v = 1, J = 1-0 and v = 1 J = 2-1 maser emission components than reported in the literature for other sources in the past. This is consistent with a model by Doel et al. (1995) and first-principle expectations for excitation of these transitions. The overall SiO morphology shows persistent features over multi-year intervals, that are very likely associated with intrinsic physical properties of the near circumstellar environment. We also find significant evidence for inhomogeneous and asymmetric localised mass-loss in this environment.

The organisation of the paper is described in what follows. The VLBA observations and their reduction are described in Section 2 and the results are presented in Section 3. The results are discussed in Section 4 in terms of the total intensity maser maps (Section 4.1). SiO maser pumping (Section 4.2), inter-comparisons of the v = 1 J = 1-0 and v = 2 J = 1-0 (Section 4.2.1) and v = 1 J = 1-0 and v = 1 J = 2-1 (Section 4.2.2) transitions respectively, and the larger-scale morphology of the circumstellar envelope (Section 4.2.3). The conclusions are presented in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

Two epochs of VLBA observations were performed in this study, conducted on 20 and 23 December 2003 (project BK103) and 15 and 19 March 2007 (project BR123). These two observations sets, under project codes BK103 and BR123, will be be denoted as epoch 1 and epoch 2 respectively, in what follows. Epoch 1 included observations of transitions 28SiO v = {0,1,2} J = 1-0 and J = 2-1, 28SiO v = {0,1,2} J = 1-0 and J = 2-1, and 30SiO v = 0 J = 1-0 and J = 2-1. Of these, only transitions 28SiO v = {0,1,2} J = 1-0 and J = 2-1 were successfully imaged (the total-intensity 28SiO v = {1,2} J = 1-0 images were presented in preliminary work by Richter et al. 2007). The other transitions had significantly lower signal-to-noise ratio and could not be imaged at sufficient dynamic range and are accordingly not included in this analysis.

To maximise the amount of time observing each transition, only transitions 28SiO v = {0,1,2} J = 1-0 and J = 2-1, 28SiO v = 1 J = 1-0 and 30SiO v = 0 J = 1-0 were subsequently included in the epoch 2 schedule. Of these transitions, we consider only 28SiO v = {1,2} J = 1-0 and v = 1 J = 2-1 here.

Images of v = 1 J = 1-0, v = 2 J = 1-0 and v = 1 J = 2-1 28SiO transitions from both epochs are presented in this paper. These lines were observed at adopted rest frequencies of 43122.03, 42820.48 and 86243.37 GHz respectively (Müller et al. 2007). The spectral windows for each line transition were centred in frequency assuming a systemic LSR velocity of +18 km s\(^{-1}\) for the target source VY CMa.

In the first epoch, the continuum extragalactic sources J0359+5057 and 3C273 were used as bandpass and phase calibrators for the 86 GHz observations, while the sources J0423-0120 and 3C273 were used in this role for the 43 GHz observations. At the second epoch, the sources 3C454.3, J0423-0120, J0609-1542 and 3C273 were used as bandpass and phase calibrators for all frequency bands.

The data were sampled using two-bit quantisation, and correlated in full cross-polarisation. In epoch 1 the 43 GHz lines were recorded in spectral windows of bandwidth 4 MHz each and those in the 86 GHz band were recorded in 8 MHz spectral windows, yielding a comparable velocity range for the transitions in each band (\(\Delta v = 27.8 \text{ km s}^{-1}\)). Analysis of the first epoch observations showed that the SiO maser emission extended beyond this observed velocity range in all of the observed transitions. The epoch 2 observations were consequently observed using double the spectral line band-
width in each band over that used in epoch 1 (8 MHz at 43 GHz and 16 MHz at 86 GHz). In the epoch 2 observations the total velocity range in the v=\{1,2\} J=1-0 transitions was determined to be approximately $\sim 40$ km.s$^{-1}$ about the systemic velocity. At the time of these observations, dual cross-polarisation correlation carried a concomitant limitation of 128 frequency channels per spectral window, and both epochs were correlated within this constraint. The nominal channel width at epoch 1 and epoch 2 was accordingly $\sim 0.22$ and $\sim 0.43$ km.s$^{-1}$ respectively.

The epoch 1 data were reduced following the techniques outlined in Kemball et al. (1992) and Kemball & Diamond (1997). These methods were refined further for high-resolution Stokes V measurement by Kemball & Richter (2011), and were then used to reduce the epoch 2 data in this work. For the total intensity and linear polarisation results reported in this paper, these two data reduction methods will not produce significantly different results. The data reduction was performed using a customised version of the Astronomical Image Processing System (AIPS$^2$). The observations are summarised in Table 1 for each transition at each epoch, listing the CLEAN restoring beam angular dimensions, the array configuration, the peak Stokes I brightness (Jy/beam) in the resultant image cube, the broadened thermal noise estimate $\sigma_{I}^{B}$ (Jy/beam) (see below), and the total time on the target source VY CMa. We note that the 86 GHz CLEAN beam sizes are larger than might be intuitively expected relative to the 43 GHz beam sizes; this is due to the absence of the outlying Saint Croix (SC) antenna in the 86 GHz observations.

The off-source RMS noise level in the maps is an underestimate of the true noise in the maps, as residual calibration and deconvolution errors are direction-dependent and frequently more pronounced close to peaks in the emission. The noise estimates for the maps were therefore empirically broadened to a Gaussian $\sigma_{I}^{B}$ established from the single-pixel deepest measured noise in the map, $I_{\text{neg}}$, and the number of pixels in the map, as described by Kemball (1992); in these channel images $\sigma_{I}^{B} = |I_{\text{neg}}|/5.295$. The noise broadening is calculated per channel as the dynamic range varies with source structure over spectral channel. The value of $\sigma_{I}^{B}$

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2 AIPS is developed and maintained by the NRAO (http://www.aips.nrao.edu)
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Figure 4. Single-contour plot of the epoch 2 total intensity v=1 J=1-0 SiO maser emission toward VY CMa, as the peak intensity over the frequency axis of the cube, at a single level of 5σ, overlaid with vectors representing the averaged fractional linear polarised emission. The vectors are drawn with a length proportional to the magnitude of the fractional linear polarisation and an orientation aligned with the absolute EVPA of the underlying linearly polarised emission. The vector length scale is 1mas = 2.5 × 10^{-2}. The image is 4096 × 4096 pixels in size, at a pixel spacing of 30µarcseconds. The synthesised beam size is 0.46 × 0.15 mas in half-power at a position angle −1.80°, N through E.

Figure 5. Single-contour plot of the epoch 2 total intensity v=2 J=1-0 SiO maser emission toward VY CMa, as per Figure 4. The image parameters are the same as Figure 4 except for the synthesised beam size, which is 0.43 × 0.14 mas in half-power at a position angle −0.94°, N through E.

The absolute electric vector position angle (EVPA) of the linear polarisation was determined through ancillary VLA observations of a primary polarisation calibrator of known polarisation position angle (Perley & Taylor 2003), along with observations of compact secondary polarisation calibrators common to both the VLA and VLBA schedules. The VLA observations of the primary polarisation calibrators were used to determine the absolute EVPA of the secondary polarisation calibrators, which, by virtue of their inclusion in the VLBA schedule, could then be used to establish the absolute EVPA of the VLBA sources (or equivalently, the residual unknown R-L phase difference at the reference antenna, assumed constant) (Kemball 1999).

The epoch 1 schedule included an auxiliary VLA observation on 20 December 2003, at which time the VLA was in B configuration. The VLA observed the primary polarisation calibrator J0521+166 (3C138) and secondary polarisation calibrators J0359+5057 in Q-band. The epoch 2 schedule included an auxiliary VLA observation on 17 March 2007. On this date the VLA was in D configuration. The calibrator 3C138 was again used as the primary polarisation calibrator in this epoch, and observed together with secondary polarisation calibrators J0646+448, J0609-1542, J0423-013 and J0542+498 in Q-band. It was not possible to perform abso-
Figure 6. Single-contour plot of the epoch 2 total intensity v=1 J=2-1 SiO maser emission toward VY CMa, as per Figure 4. The image parameters are the same as Figure 4, except for the synthesised beam size, which is 0.42\times 0.09 mas in half-power at a position angle \(-16.35^\circ, \text{N through E.}\)

Figure 7. Overlaid epoch 1 total intensity contour plots of the SiO maser transitions v=1 J=1-0 (blue), v=2 J=1-0 (green), and v=1 J=2-1 (red) taken as the peak over frequency in each transition. These images have been astrometrically aligned as described in the text. A single contour is plotted for each transition, at a level of 10\(\sigma_B\) (see Table 1).

3 RESULTS

Single-contour plots of the total intensity emission for each transition, as the peak over frequency across each image cube, and overlaid with vectors oriented at the EVPA and proportional in length to the underlying linearly polarised intensity, are shown for each data set in Figures 1 to 6. For the lower-sensitivity epoch 1 images, the single total intensity contour level was chosen as 10\(\sigma_B\). For the epoch 2 images, a contour level of 5\(\sigma_B\) was used.

Absolute astrometric information about the source is lost during the data reduction process, due to the use of phase self-calibration (Thompson et al. 2004) (Equivalently, the origin of each of Figures 4 to 6 is set by the choice of phase-reference channel and these processed maps are not intrinsically aligned). The maser maps for each transition within each epoch were therefore aligned using a cross-correlation method, as described in Appendix A. The uncerainty in the epoch 2 map alignment is estimated to be <0.05 mas. The cross-correlation method required manual refinement for the epoch 1 maps, which had much fewer overlapping components. Assuming the correct peak has been selected, the uncertainty in the epoch 1 map alignment is also estimated to be <0.05 mas. In the alignment analysis, the epoch 2 deconvolved images were all restored with the same v=1 J=1-0 beam, whereas the epoch 1 images were deconvolved with the intrinsic beam sizes listed in Figures 1 to 3; this is not believed to substantially affect the alignment method.

The aligned total intensity maps are shown in Figures 1 and 3. The epoch 2 v=1 J=1-0 emission is shown separately in Figure 3 with contours colour-coded by velocity channel. Enlarged plots of of several regions of the epoch 2 overlay map are shown in Figures 10 and 11.

For the epoch 2 overlaid transition maps in Figures 8, 10 and 11, the deconvolved maps in each transition were restored with the same v=1 J=1-0 beam size. This aids their component-level interpretation (see Figures 10 and 11 and associated discussion in the text). The single panel epoch 1 overlay of multiple transitions (Figure 7) uses the intrinsic beam sizes in Figures 1 to 3, as discussed above.

4 DISCUSSION

4.1 Intensity morphology

For all of the total intensity maps presented in Figures 1 to 6, the emission falls within a region ~ 100 \times 100 mas in angular extent. Adopting a stellar diameter of 18.7 mas and a dust formation radius of ~ 40 – 50 mas (Danchi et al. 1994; Monnier et al. 2004), most of the observed emission is located within a few stellar radii from the star, and within the dust formation radius.

Previous images of the SiO maser emission towards VY CMa (Miyoshi et al. 1994; Miyoshi 2003; Shibata et al. 2004; Richter et al. 2007; Choi et al. 2008; Zhang et al. 2012) show radially thicker and less well-defined rings than...
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Figure 8. Overlaid epoch 2 total intensity contour plots of the SiO maser transitions $v=1$ $J=1-0$ (blue), $v=2$ $J=1-0$ (green), and $v=1$ $J=2-1$ (red) taken as the peak over frequency in each transition. These images have been astrometrically aligned as described in the text. A single contour is plotted for each transition, at a level of $5\sigma_B$ (see Table 1). The regions R1, R2, R3 and R4 shown in the epoch 2 map are discussed in further detail in the text.

those often observed around AGB stars (Diamond et al. 1994). The total intensity maps presented here follow the same trend: no clear ring structure is visible in the epoch 1 maps, and the epoch 2 maps appear to show a sparse, wide ring.

The inner limit of the epoch 2 maser ring in the $v=1$ $J=1-0$ transition is not well defined, due to gaps in the emission. The maximum radial extent is $\sim 60$ mas in the northeast, with most of the emission around the rest of the ring falling within a radial extent of $\sim 40$ mas from the approximate center of the emission. The epoch 2 $v=1$ $J=1-0$ maser distribution is very similar to images of the same transition presented in Zhang et al. (2012), the most contemporaneous of which was observed about a month apart from our epoch 2. Multiple features can be visually matched between the epoch 2 maps presented here and the maps presented by both Choi et al. (2008) and Zhang et al. (2012). Both the $v=1$ and $v=2$ $J=1-0$ images display concentrated emission regions in the east and northeast (see regions R1-R4 in Figure 3). One of the most striking features in the images is an $\sim 14$ mas elongated feature in the eastern part of the projected ring (R3 in Figure 8 and Figure 11), which is visible in maps presented by both Choi et al. (2008) and Zhang et al. (2012). These individual regions of emission are discussed in more detail in subsequent sections.

Figure 9. Epoch 2 total intensity contour plot of the SiO maser transition $v=1$, $J=1-0$, color-coded by line-of-sight velocity in the LSR frame as shown in the colour bar below the figure. The contour levels are $-2$, $2$, $10$, $20$, $40$, $60$, and $80\%$ of the peak brightness of 22.15 Jy/beam.

The fraction of the total emitted maser flux recovered in the VLBA images can be determined through comparison of the interferometer autocorrelation spectra and the summed interferometric Stokes $I$ spectra obtained from the final image cubes. These spectra are shown for each epoch in Figure 12. In epoch 1, for the $v=1$ $J=1-0$ and $v=2$ $J=1-0$ lines $\sim 50\%$ and $\sim 75\%$ respectively of the integrated intensity from the autocorrelation spectra is recovered in the VLBA Stokes $I$ images. The fraction recovered in the epoch 1 $v=1$ $J=2-1$ line is much lower, at $\sim 14\%$. In epoch 2, approximately $35\% - 40\%$ of the total emission from the $J=1-0$ lines were recovered in the VLBA images. For the epoch 2 $v=1$ $J=2-1$ line, approximately $22\%$ of the total emission was recovered interferometrically.

The $J=1-0$ fractions are consistent with VLBA observations of Cotton et al. (2006, 2009a,b, 2010a,b) and Soria-Ruiz et al. (2004, 2005, 2006, 2007), who observed $v=1$ and $v=2$ $J=1-0$ SiO maser emission towards a number of late-type stars, over multiple epochs in some cases. These observations report flux recovery of a few tens of percent up to almost all of the single dish flux, varying across the spectra and over different epochs.

The lower fraction of recovered flux for the $J=2-1$ line observed here is also consistent with previous VLBA obser-
vations of this transition, which show typical maximum flux recovery of $\sim 10–15\%$ (Soria-Ruiz et al. 2004, 2005, 2007). A notable exception is Soria-Ruiz et al. (2006), who recover up to $\sim 50\%$ of the $v=1$ $J=2-1$ SiO maser emission towards TX Cam, for individual features in the spectrum.

Missing flux can be attributed to diffuse emission, on a scale too large to be detected by the VLBA, or to numerous low intensity maser spots which fall below the noise level of the images (Gray et al. 2009). By definition, the problem of missing flux impacts comparative studies at different frequencies, because the spatial scales recovered may unavoidably differ per transition. The differing brightness temperature sensitivity does not introduce a systematic spatial offset between transitions however, and therefore does not impair our key conclusions regarding the degree of spatial alignment and superimposition.

Emission at larger angular scales than the reciprocal of the shortest baseline (in wavelength-units) is not visible to interferometers (Thompson et al. 2004). The shortest unprojected VLBA baseline is 236 km, between antennas Los Alamos and Pie Town, which corresponds to $\sim 6.1$ mas at 43 GHz and $\sim 2.6$ mas at 86 GHz. Emission on scales between $\sim 3$ and 6 mas may therefore be detected by the 43 GHz observations presented here, but not by the 83 GHz observations. For these data, the brightness temperature sensitivity at 43 GHz is approximately double that at 86 GHz.

The fact that more large-scale emission is filtered out in the 86 GHz observations is reflected in the recovered autocorrelation emission fraction, which is considerably lower at 86 GHz for both epochs. However, in the case of the extended northeastern region of emission in the epoch 2 $J=1-0$ maps, an argument can be made that the absence of $J=2-1$ emission in the northwest is real. The epoch 2 autocorrelation and summed interferometric spectra show a spectrally-wide feature spanning about 15 km/s about the central velocity, which corresponds primarily to the more extended region of emission in the northeast of the $J=1-0$ epoch 2 maps. This is most clearly visible in Figure 9, a contour plot of the $v=1$ $J=1-0$ maser emission colour-coded by velocity. The

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$^3$ The epoch 2 $v=1$ $J=1-0$ observation did include one VLA antenna, providing a shorter baseline between Pie Town and the VLA antenna, but the VLA data were flagged out.

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Figure 10. As for Figure 8 but showing the SiO maser transitions $v=1$ $J=1-0$ (blue), $v=2$ $J=1-0$ (green), and $v=1$ $J=2-1$ (red) for epoch 2, for regions R1 and R2.

Figure 11. As for Figure 8 but showing the SiO maser transitions $v=1$ $J=1-0$ (blue), $v=2$ $J=1-0$ (green), and $v=1$ $J=2-1$ (red) for epoch 2, for regions R3 and R4.
Wide feature is not observed in the J=2-1 autocorrelation or summed interferometric spectra.

4.2 SiO maser pumping models

As discussed earlier, models for circumstellar SiO maser excitation rely either on radiative pumping, collisional pumping, or a combination of the two (Lockett & Elitzur 1992, Bujarrabal 1994). Which predominant pumping mechanism is driving circumstellar SiO masers remains an issue of some debate (Desmurs et al. 2000, Soria-Ruiz et al. 2004, Gray et al. 2009). In this section we consider the relative characteristics of the v=1 J=1-0, v=2 J=1-0 and v=1 J=2-1 SiO maser emission, presented in Figures 1 to 11 as observational tests on the SiO maser pumping models discussed earlier.

4.2.1 v=1 J=1-0 and v=2 J=1-0

Both epochs of VY CMa observations presented here show overlap between the v=1 and v=2 J=1-0 emission. In the epoch 1 observations there are several v=2 features with no coincident, or even nearby, matching v=1 features. However, during epoch 1 the noise level of the v=2 J=1-0 map was considerably lower than that of the v=1 J=1-0 map (Table 1), so the more limited overlapping v=1 emission in epoch 1 is likely an SNR artifact.

In the epoch 2 observations, where the v=1 and v=2 J=1-0 maps have similar noise levels (Table 1), the v=2 emission is located almost exclusively in a subset of v=1 emission regions. This is consistent with the Gray & Humphreys (2000) hydrodynamical model, which predicts a thicker maser ring for the v=1 J=1-0 line, with the v=2 masers arising in a subset of the v=1 conditions.

In the extended regions of emission R1 and R2 (Figure 8 Figure 10) the overlapping v=1 and v=2 J=1-0 maser emission is morphologically very similar. Most of the v=2 emission appears to follow the v=1 emission closely in these regions, occupying the same regions, or subsets of regions, as those exhibiting v=1 emission. The extensive overlap in R1 especially argues either for a predominantly collisional pumping mechanism at work in this region, or if the pumping mechanism is radiative, then the overlap may be caused by the H$_2$O line overlap mechanism coupling the v=1 and v=2 J=1-0 lines (Soria-Ruiz et al. 2004). However, the linear polarisation is weak in region R1. Statistically significant linear polarisation is only measured in four v=1 J=1-0 features, and no v=2 J=1-0 features, in region R1 (the statistical significance is measured using the broadened noise in Stokes I, Q and U defined above.) The four features which do display linear polarisation in v=1 J=1-0 are all less than 10% polarised. The overall maximum linear polarisation across all transitions is $\sim$ 45% in epoch 2. The component-level polarisation characteristics will be presented in greater detail in a future publication.

Linear polarisation is a natural characteristic of anisotropic radiative pumping from a central star (Bujarrabal & Nguyen-Q-Rieu 1981). This effect would also tend to be weaker further from the star, as stellar radiation is diluted over a greater volume. So the wide radial extent of the maser emission in region R1 also argues against strong anisotropic radiative pumping in this region.

The close coupling of the v=1 and v=2 J=1-0 maser emission in R1 may still be evidence of a H$_2$O line overlap impacting the pumping scheme, but possibly in the context of a predominantly collisional pumping mechanism. In R2, if the v=1 and v=2 J=1-0 emission overlap is primarily due to the H$_2$O line overlap mechanism then the observed spatial overlap between the v=1, J=1-0 and v=1, J=2-1 lines would only occur under a very restricted set of envelope conditions (Soria-Ruiz et al. 2004).

The component spectrum for the elongated feature R3 (Figure 8 and Figure 11) is shown in Figure 13. The v=2 J=1-0 frequency axis in Figure 13 is shifted by two channels ($\sim 0.86$ km.s$^{-1}$) to account for an observed $\sim 2$ channel frequency offset between the positions of maser features in the v=1 and v=2 J=1-0 transitions. The offset is likely due to errors in the assumed rest frequencies of these transitions. The rest frequencies used in the data reduction were taken from “The Cologne Database for Molecular Spectroscopy” (Müller et al. 2005), whereas the images of overlapping components are more consistent with the frequencies catalogued in the “Spectral Line Atlas of Interstellar Molecules” (Remijan et al. 2007). High precision velocity in-
formation is not required by this work, so precise corrections for the offset were not attempted.

The $v$=2 $J$=1-0 emission in R3 is located within two main subsets of the $v$=1 $J$=1-0 emission region: near the region of peak intensity, and at the inner end of the feature, closest to the star. Where the $v$=1 and $v$=2 $J$=1-0 emission overlaps, it is expected that the $v$=2 emission will occur closest to the star, under a radiative pumping scheme (Desmurs et al. 2004), or in higher density conditions (also presumably closer to the star), under a collisional pumping scheme (Doel et al. 1995; Gray & Humphreys 2000). The $v$=2 emission at the inner end of the long feature can therefore be explained by either pumping mechanism. The overlapping region in the peak intensity centre of the R3 may be due to the coherent path length of the maser emission being longest in this region, allowing significant amplification for all three maser transitions. Alternatively, the overlapping region of emission in R3 may be a result of competitive gain, where transitions in different vibrationally-excited states become coupled as the maser emission saturates (Doel et al. 1994). The effect of saturation on maser polarisation varies between maser polarisation models, with anisotropic pumping models showing linear polarisation decreasing with saturation (Nedoluha & Watson 1990), some maser polarisation modelling showing increasing linear polarisation with saturation (Western & Watson 1984) and other modelling showing that the level of linear polarisation is the same in the unsaturated and saturated regimes, all other factors being equal (Elitzur 1991). We note here that feature R3 has statistically significant linear polarisation in all three maser transitions. We note here that feature R3 has statistically significant linear polarisation in all three maser transitions. We note here that feature R3 has statistically significant linear polarisation in all three maser transitions.

4.2.2 $v$=1 $J$=1-0 and $v$=1 $J$=2-1

As noted earlier, simultaneous measurements of the spatial overlap of $v$=1, $J$=1-0 and $v$=1, $J$=2-1 SiO masers are limited in number due to technical challenges and show mixed results in terms of the degree of spatial overlap and $v$=1 $J$=1-0 counterparts may be indicative of radiative pumping of these masers. Under the predominantly radiative pumping model of Bujarrabal (1994), $v$=1 $J$=2-1 emission is stronger than the $v$=1 $J$=1-0 emission over most of the range of envelope conditions they investigated, with a greater difference at lower densities. However, as noted above, this rel-
4.3 Circumstellar envelope morphology

The distribution of circumstellar SiO maser features is variable over time (Diamond & Kemball 2003), with individual maser features appearing, evolving, and disappearing, as envelope conditions and excitation conditions change. The distribution of maser features in single-epoch maps should therefore not be over-interpreted. Gaps in SiO maser rings, for example, can arise out of purely random maser spot configurations (Gray et al. 2004).

However, the trend of the v=1 and v=2 J=1-0 maser emission being concentrated predominantly to the east of VY CMa (see Figures 7 and 8) persists over many VLB observations of this source (Miyoshi 2003; Choi et al. 2008; Zhang et al. 2012) and is seen also in the v=1 J=1-0 VLA map of Zhang et al. (2012). The trend of more uniformly distributed v=1 J=2-1 emission, with some concentration in the southwest, is also observed in maps published earlier by Shibata et al. (2004).

The persistence of these trends indicates that they may be connected to longer-term physical characteristics of the near-circumstellar envelope of VY CMa.

Many authors have suggested that VY CMa is surrounded by a circumstellar disk. Possible origins of a circumstellar disk include excess dust formation and mass loss above magnetic cool spots in equatorial stellar regions (Soker & Clayton 1999), the effect of rotation (Wittkowski et al. 1998), the presence of a binary companion (Cruzalébes et al. 1998), or that a pre-main sequence disk has survived throughout the subsequent stellar evolution of VY CMa (Richards et al. 1998; Kastner & Weintraub 1998).

The observed distribution of maser emission may be consistent with a disk geometry if the western and southwestern emission emanates from the polar region, where the flow of circumstellar material is faster and the gas is less dense. This would limit the line of sight velocity coherence, leading to the more compact maser features observed in this region. The relatively large number of v=1 J=2-1 maser features in the polar region relative to the J=1-0 masers may be due to favourable envelope conditions for v=1 J=2-1 maser emission, as discussed in the previous section.

In this picture, the more extended north-eastern regions of epoch 2 J=1-0 emission which lie near the stellar velocity may fall in the equatorial plane and may be probing the disk around the star. This is illustrated in Figure 9 which shows the the velocity structure of the epoch 2 v=1 J=2-1 image. The extended emission in region R1, as well as the emission further from the star in the northeast, displays a velocity gradient away from the stellar velocity with distance from the star, consistent with a location in the forward lobe of a disk. The large extent of the emission in R1 in particular indicates favourable conditions for the J=1-0 masers in this region. This may imply greater velocity coherence in this region, or temperature and density conditions favourable to these masers.

However, the morphology of the SiO maser emission can be explained in a variety of ways outside of a bipolar envelope model. Zhang et al. (2012) recently published a proper motion study of four epochs of v=1 J=1-0 SiO maser emission towards VY CMa. The SiO masers display slow, quasi-spherical outflow, with no strong evidence for a bipolar outflow. They model six observed spoke-like SiO maser features using a ballistic-orbit model, which provides a good fit for most of the features. However, they note that the ballistic model assumes that the maser features are radially aligned, which is at odds with the expansion model they fit to the proper motion of the features. They suggest that a more realistic modelling of the complex near-circumstellar envelope may require acceleration driven by pulsation or giant convective cells and the use of a hydrostatic inner envelope (Zhang et al. 2012).

A number of recent observations of VY CMa have shown that the circumstellar envelope is highly inhomogeneous and mass-loss from the star may occur in localised events (Smith et al. 2001; Humphreys et al. 2003; Smith et al. 2009). The variable characteristics of the VY CMa SiO maser emission across the circumstellar envelope may be evidence of this localised enhanced mass-loss from the star. In this context, the sparser region of more compact masers in the southwest may be a region of enhanced mass loss, where the circumstellar material is more turbulent. This is consistent with the near-infrared Keck aperture-masking images of Monnier et al. (1999) which shows extended emission to the south and southwest of the star, possibly indicative of concentrated mass-loss in these directions.

5 CONCLUSIONS

In this paper, we have presented VLBI images of the v=\{1,2\} J=1-0 and v=1, J=2-1 SiO maser emission in total intensity, total fractional linear polarisation, and electric vector posi-
tion angle toward the supergiant star VY CMa. The total intensity images in separate transitions were spatially aligned using a cross-correlation technique. The source VY CMa was chosen because of its brightness across multiple SiO maser transitions. In the current paper we have examined the spatial overlap of individual features in the separate transitions, their relative brightness, and implications for maser pumping. In addition, we have analysed the observations as a whole to study the overall morphology of the near-circumstellar environment of VY CMa.

Our conclusions from the current work are:

1) In epoch 2, in which the transition sensitivities are similar, the individual $v=2, J=1-0$ maser components are almost always found within a subset of the $v=1, J=1-0$ emission regions, and in the case of image region R1, with very close morphological similarity. This is consistent with the hydrodynamical model of Gray & Humphreys (2000). Although there are differences in overlap conditions across the source for these two transitions in detail, overall this finding in the current work is more supportive of collisional pumping rather than radiative pumping including an $H_2O$ line overlap.

2) The $v=1 J=1-0$ and $v=1 J=2-1$ epoch 2 maps display a greater level of coincident maser features than has previously been reported for these two transitions. However, in contradiction to the Humphreys et al. (2002) model prediction, the $J=2-1$ emission is weaker than the $J=1-0$ emission in most cases for the coincident features. This behaviour is consistent with the Doel et al. (1993) model, where the relative weakness of the $v=1 J=2-1$ emission implies a low density constraint.

3) The overall total intensity morphology of the SiO maser emission toward VY CMa exhibits long-lived large-scale features that persist over at least several years. They are very likely associated with the intrinsic physical structure of the near-circumstellar environment. Current data do not strongly constrain the bipolarity (or non-bipolarity) of the bulk kinematics, but there is evidence for local inhomogeneous or asymmetric mass-loss in this environment.

4) The current work demonstrates that, as well as providing constraints on maser pumping models, simultaneous observations of SiO maser emission in multiple transitions and full polarisation at the component level is a promising means to investigate both the theory of astrophysical masers as well as the environments of late-type evolved stars. Features such as R3 in epoch 2 demonstrate the power of this approach, and will be discussed in further detail in future papers.

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APPENDIX A: MAP ALIGNMENT

The SiO maser images from different transitions can be aligned by cross-correlating the two-dimensional peak intensity maps of the Stokes $I$ emission. The peak of the two-dimensional cross-correlation function gives the offset required to maximise the spatial correlation of the two maps. For increasing spatial overlap and structural similarity between the maps being aligned the central peak of the cross-correlation product will be increasingly compact and well-defined.

The measured offset is assumed to be the physical skyplane offset between the maser emission from the two maps. This assumption is justified if there are no systematic global linear offsets between the emission in the cross-correlated maps. A global linear offset is not scientifically expected, as there is no large scale linear effect across the circumstellar envelope which could lead to an overall offset between emission from the different transitions. From the circumstellar geometry of the maser emission, any possible offsets are more likely caused by effects with radial dependence. These might include maser pumping dependencies either on density or stellar radiation intensity.

When performing the cross-correlation alignment, it was found that extremely high intensity maser spots could bias the spatial correlation; in this case the peak in the correlation product preferentially aligns the two highest spots in the two input images. In order to mitigate this, the peak intensity input maps were transformed to have unity intensity where the original intensity exceeded a specified cutoff level, and zero below this cutoff. The cutoff values were set to the contour levels shown in Figures 1 to 6, ten times the maximum broadened noise variance $\sigma_I$ of the Stokes $I$ cubes for the epoch 1 data sets, and five times the maximum $\sigma_I$ for the epoch 2 data sets. The maser maps were then cross-correlated pair-by-pair, and sub-pixel level offsets were determined through Gaussian fits to the dominant peak of each cross-correlation function.

Examples of the cross-correlation functions are shown
in Figure A1. These plots show the regions around the dominant peaks in the cross-correlation functions; the cross-correlation function was calculated for the full extent of the images. Figure A1 (left) shows the cross-correlation function for the $v=1 J=1-0$ and $v=1 J=2-1$ images from epoch 1. This is an example of a case where the correlation method performs poorly, as there is not sufficient overlapping emission in the maps to provide a clear dominant compact peak in the cross-correlation product. In this instance the results of the cross-correlation method were refined by manually testing the cross-correlation product peaks to determine which peak is the correct offset between these images, considering the frequency distribution of the emission as well as the maximum intensity Stokes $I$ image by visual inspection.

The uncertainty in the offset is estimated as the ratio of the fitted Gaussian FWHM of the peak and the SNR of the source, following Phillips et al. (2003). The minimum individual-channel SNR across all of the data cubes was $\lesssim 4$, and the overall maximum SNR was $\gg 100$. For the epoch 2 cubes the maximum SNR values were $\gtrsim 400$. The uncertainty in the epoch 2 map alignment is therefore estimated to be $< 0.05$ mas. Assuming the correct peak has been selected in the epoch 1 alignment, the uncertainty is also estimated to be $< 0.05$ mas for epoch 1.