A phase-dependent comparison of the velocity parameters of SiO $v = 1$, $J = 1–0$ and $J = 2–1$ maser emission in long-period variables

B. T. Indermuehle$^1$ and G. C. McIntosh$^2$

$^1$CSIRO Astronomy and Space Science, PO Box 76, Epping, NSW 1710, Australia

$^2$Division of Science and Mathematics, University of Minnesota, Morris, 600 East 4th Street, Morris, MN 56267, USA

Accepted 2014 April 11. Received 2014 March 9; in original form 2013 August 8

ABSTRACT

We have examined the relationship between the velocity parameters of SiO masers and the phase of the long-period variable stars (LPVs) from which the masers originate. The SiO spectra from the $v=1, J=1–0$ (43.122 GHz) and the $v=1, J=2–1$ (86.2434 GHz) transitions have been measured using the Mopra Telescope of the Australia Telescope National Facility. 121 sources have been observed including 47 LPVs contained in the American Association of Variable Star Observer Bulletin. The epoch of maxima and the periods of the LPVs are well studied. This data base of spectra allows for phase-dependent comparisons and analysis not previously possible with such a large number of sources observed almost simultaneously in the two transitions over a time span of several years. The velocity centroids (VCs) and velocity ranges of emission (VRs) have been determined and compared for the two transitions as a function of phase. No obvious phase dependence has been determined for the VC or VR. The results of this analysis are compared with past observations and existing SiO maser theory.

Key words: Masers.

1 BACKGROUND

1.1 VCs and VRs

The determination of the velocity centroid (VC) and velocity ranges of emission (VR) were recently presented (McIntosh & Indermuehle 2013a) and will only be briefly reviewed here. Mathematically, the VC is the sum of the antenna temperature $T_A$ in each velocity channel times the velocity with respect to the local standard of rest $v_{lsr}$ of the velocity channel over the range of emission divided by the sum of the $T_A$ in each velocity channel over the range of emission as shown:

$$VC = \frac{\sum(T_A v_{lsr})}{\sum T_A}. \hspace{1cm} (1)$$

The summation extends over the range of emission.

The VR is calculated to be the region where the $T_A$ exceeds three times the standard deviation of the antenna temperature of the background noise. The standard deviation is determined from velocity channels far away from the emission range of the source.

McIntosh & Indermuehle (2013a) examined the VCs and VRs of the SiO maser transitions without regard to the phase of the star. In this work, we found that the VR$_{1\rightarrow0}$ was generally broader than the VR$_{2\rightarrow1}$, 6.4 to 4.2 km s$^{-1}$, respectively. The VC$_{1\rightarrow0}$ are slightly more positive than the VC$_{2\rightarrow1}$. These differences indicate that the $J=2–1$ ($J_{1\rightarrow0}$) occurs in a dynamically different region of the circumstellar environment than the $J=2–1$ ($J_{2\rightarrow1}$). This conclusion is consistent with the observational results of Soria-Ruiz et al. (2004, 2007). The VC is a well-suited parameter to compare our single-dish observations to very long baseline interferometry (VLBI) observations, as it is weighted to the brightest emission. This effect is apparent in the figures B1–B3 in Assaf et al. (2011). Kim, Cho & Kim (2014) have compared SiO and H$_2$O maser emission from 401 evolved stars. They find that SiO emission is less dependent on the optical phase than the H$_2$O masers. While this is a relative conclusion only, it indicates no strong phase relationship for the VR, a finding which complements our own.

Phillips et al. (2003) concluded that $J_{1\rightarrow0}$ and $J_{2\rightarrow1}$ emission can form at comparable radii and in related columns of gas, although their VLBI maps show few overlaps between the two transitions. Recent theoretical developments vary in predicting the radii at which the $J_{1\rightarrow0}$ and $J_{2\rightarrow1}$ emission occur. Gray et al. (2009) have the $J_{2\rightarrow1}$ emission at larger or smaller radii than the $J_{1\rightarrow0}$ emission depending on the phase. Yun & Park (2013) show no discernible difference in the radii at which the masers originate at any phase presented.

1.2 Phase determination

The phase of the star is the optical phase. It is determined by subtracting the Julian day number of the most recent stellar maximum from the Julian day number of the observation and dividing by the...
stellar period. The phase varies from 0 to 1. The stellar maxima and periods were obtained from the AAVSO Bulletin 74 (AAVSO 2011). Stellar periods were added or subtracted from the Bulletin 74 maxima as needed to determine the most recent maxima. Table 1 gives the stellar periods used for the sources.

1.3 Maser velocity parameters

Gray et al. (2009) investigated the dynamics of the circumstellar region in which the SiO masers originate and have provided the most thoroughly developed theory for the maser spectra in long-period
variable stars (LPVs) from phase 0.1 to 0.4. They model and depict a shock travelling out from the star generating different velocities, redshifted or more positive and blueshifted or more negative, at different distances from the star. As the shock travels out, the velocities change as a function of distance from the star and phase. Gray et al. (2009) predicted a phase-dependent VR_{1\rightarrow0} varying from about 8 to 13 km s\(^{-1}\). The VR_{2\rightarrow1} varies from about 7 to 12 km s\(^{-1}\). The difference between the VRs in the two transitions is phase dependent and difficult to quantify from the information presented, but the VR_{1\rightarrow0} always appears to be greater than the VR_{2\rightarrow1}. In their fig. 12, they show that at a phase of 0.4 only the J_{1\rightarrow0} emission should be present, at a phase of 0.3 the maximum VR should occur in the J_{1\rightarrow0} emission, several km s\(^{-1}\) broader than the emission at a phase of 0.1, and the VC_{1\rightarrow0} should undergo a redward shift with increasing phase. No shift in the peak or VC is indicated for the J_{2\rightarrow1} transition.

Yun & Park (2013) have developed a coupled escape probability model for SiO maser emission. They present several figures indicating the VR in the J_{1\rightarrow0} and J_{2\rightarrow1} transitions. In their fig. 7, the J_{2\rightarrow1} emission is consistently broader than the J_{1\rightarrow0} emission, and the VR_{1\rightarrow0} and VR_{2\rightarrow1} vary by a factor of more than 5 over the stellar period. The emission at their epoch 6 is several times broader than the emission at the other epochs depicted. For their epoch 11, the J_{1\rightarrow0} is very weak and narrow. Since different distances from the star are affected differently by the proposed shock travelling out from the star, it is reasonable to expect that masers forming at different distances from the star will exhibit different VRs and slightly different VCs. The observations of the velocity parameters of the emission provide information on the locations as well as the motion of the masing material.

2 OBSERVATIONS

The 22 m Mopra radio telescope is located in New South Wales, Australia. At Mopra, each maser source is first pointed on to ascertain adequate positioning inside the beam. The observations are then executed as 16 cycles on and 16 cycles off observation, thus lasting 64 s per on/off pair. For J_{2\rightarrow1} observations, the rms noise was about 1.8 Jy. For J_{1\rightarrow0} observations, the rms noise was about 0.6 Jy. The velocity resolution was 0.23 km s\(^{-1}\) (J_{1\rightarrow0}) and 0.12 km s\(^{-1}\) (J_{2\rightarrow1}).

The Mopra monitoring programme observes 121 sources since 2008 and is described in the data catalogue by Indermuehle et al. (2013). LPVs, semiregular variables, irregular variables, OH-IR stars, and the Orion SiO maser source were observed approximately monthly in J_{1\rightarrow0} and J_{2\rightarrow1} between 2008 and 2012. LPVs were chosen for this analysis because they present a relatively uniform collection of sources and a group of stars for which theoretical models of the SiO maser emission have been developed. For the 47 LPVs observed, the stellar velocity, the number of observations in each transition, and the number of observations of both transitions within 24 h are given in Table 1. The sources are listed in the AAVSO Bulletin (AAVSO 2011) as LPVs with well-determined maxima and periods. Non-detections of the sources have not been included in the following analysis.

3 VELOCITY PARAMETERS AND RESULTS

3.1 VC comparison

Since observations indicate and theories predict that the J_{1\rightarrow0} and J_{2\rightarrow1} masers exist at different distances from the star, a phase-dependent difference in the VC_{2\rightarrow1} and VC_{1\rightarrow0} might exist as the proposed shock propagates outwards from the star. Fig. 1 shows the VC_{2\rightarrow1} VC_{1\rightarrow0} versus phase. No phase dependence of the VC difference is obvious. There are also predictions that the VC should have a redward shift in the VC_{1\rightarrow0} versus phase (Gray et al. 2009). Fig. 2 shows the VC_{1\rightarrow0} at the phase indicated minus the VC_{1\rightarrow0} at the earliest observed phase during a stellar cycle (normalized to the earliest observed phase). At least, five observations of the source during an individual phase period had to be available to include the information in this analysis.

Cho, Kaifu & Ukita (1996) subtracted the stellar velocity from the ‘mean velocity’ of the J_{1\rightarrow0} and the SiO v=2, J=1\rightarrow0 emission from 43 late-type stars. They concluded, based on the data shown in their fig. 5, ‘The mean velocity of the 28 SiO v=1 and v=2 masers as a function of the optical phase shows that the redshifted emission is dominating during the phases from 0.3 to 0.8, while the blueshifted emission appears from phase 0.85 and is dominating during phases 0.0–0.2 (or 1.0–1.2).’ Fig. 4 shows the results of a similar analysis with our data subtracting the stellar velocity from the VC. We have approximately 10 times as many data points as...
Figure 3. As in Fig. 2 for the VC$_{2\rightarrow1}$ data. 298 points are included in the plot.

Figure 4. The difference between VC and $V_{\text{star}}$ versus phase. The 277 VC$_{1\rightarrow0}$ points are indicated by circles. The 214 VC$_{2\rightarrow1}$ points are indicated by squares.

Cho et al. (1996). No phase-dependent shift of the VCs with respect to the stellar velocity is obvious.

3.2 VR comparison

Many observers have concluded that the SiO maser-integrated flux density is a maximum at a stellar phase of between 0.05 and 0.2 (Hjalmarson & Olofsson 1979; Pardo et al. 2004). Alcolea et al. (1999) stated that there was a variable contrast of the integrated flux density over the period of the stars. The contrast was defined as the ‘intensity ratio between consecutive maximum and minimum epochs’. The average contrast was approximately three but ranged from 4 to 20 for Mira. These conclusions have generally been based on observations of the brightest maser sources and all the sources were not LPVs. While the integrated flux density versus phase has been well examined, the VR has not been previously examined as a function of stellar phase. Figs 5 and 6 show the velocity ranges of the $J_{1\rightarrow0}$ and $J_{2\rightarrow1}$ transitions, respectively. The VR does not reproduce the phase dependence of the integrated intensity. There is no obvious maximum or minimum in the VR of either transition versus phase. The VR$_{1\rightarrow0}$ generally exceeds the VR$_{2\rightarrow1}$ as stated in McIntosh & Indermuehle (2013a). Fig. 8 in Kim et al. (2014) shows the full width at zero power versus optical phase for SiO masers, which is a similar metric as we are employing and showing in our Fig. 5. It is interesting to see that they do not find a strong correlation either between optical phase and peak emission from SiO masers in their large sample of 401 late-type stars.

4 FUTURE WORK

In the future, the Mopra SiO maser data base will be used to look for periodicities in velocity parameters of individual sources. L2 Puppis, a semiregular variable, has been examined and a 139 d periodicity in the SiO VC has been found (McIntosh & Indermuehle 2013b). This periodicity likely indicates a non-radial pulsation of the star. Periodicities in the velocity parameters of the star could indicate various interesting phenomena: planets, non-radial effects, or other asymmetries in the circumstellar environment. The case of L2 Puppis is similar to that of findings by a VLBI study of TX Cam (a source too far north to be in the Mopra catalogue) in which periodicity in SiO emission has been observed by Gonidakis, Diamond & Kemball (2013).

5 CONCLUSIONS

The Mopra data base provides the first large data set of LPV SiO maser spectra (essentially simultaneous observations in $J_{2\rightarrow1}$ and $J_{1\rightarrow0}$ from 2008 until 2012) to allow the comparison of the VCs and VRs versus phase with theoretical model predictions. The velocity comparisons extracted from these observations will inform
and constrain the development of future models of the circumstellar environment and maser dynamics. The analysis of the VCs and VRs of 47 LPVs as a function of phase shows no shifts or variations that indicate the passage of a shock through the circumstellar material.

ACKNOWLEDGEMENTS

We would like to acknowledge the efforts of Remi Patriot, Chad Reverman and Emma Molden in the data reduction that forms the basis for this paper and the support of the University of Minnesota, Morris, in this work. The Mopra radio telescope is part of the Australia Telescope National Facility which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. The University of New South Wales Digital Filter Bank used for the observations with the Mopra Telescope was provided with support from the Australian Research Council.

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