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VERA Observations of SiO Masers in the Symbiotic Star R Aquarii

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Abstract

We present phase-referenced maps of the SiO maser transitions $v = 1$ $J = 1$–0 and $v = 2$ $J = 1$–0 from the symbiotic stellar system R Aquarii, which hosts an evolved AGB star plus a hot companion. Observations were performed at two epochs: 2004.98 and 2005.98. Accurate absolute coordinates and proper motions of the emission centroid were obtained; the errors expected for these parameters are also given. We compare the VERA data with the previous astrometry by Hipparcos. This represents a possibility to improve the orbital parameters of the system in a different way than that done before. Thanks to our accurate astrometry, we have also estimated the percentage of spot coincidences between both maser transitions, a parameter that has been proposed to be relevant to discriminate between different maser pumping schemes. Although the overall distributions of both lines are always similar, the spots are rarely coincident, in a percentage ranging between 3% and 20% of the cases. The lack of systematic coincidence favors, in principle, radiative pumping. However, we argue that no firm conclusion can be reached due to a lack of models that include an overlap of rovibrational lines, and that accurately address the coincidence of very intense spots of different maser transitions.

Key words: radio lines: stars — masers — technique: interferometric — stars: AGB — stars: circumstellar matter, mass-loss

1. Introduction

R Aquarii is a symbiotic stellar system including an M-type Mira-like variable and a hot companion. The distance to this object is ∼200 pc, based on a Hipparcos parallax measurement.

The binary orbit is characterized by a distance between stars of about 2×10^{14} cm (Hollis et al. 1997; McIntosh & Rustan 2007) and, according to Hollis et al., an axis P.A. $\sim 0°$. An accretion disk is formed around the compact component, giving rise to prominent jets being detected in several wavelengths (e.g., Michalitsianos et al. 1988; Kellogg et al. 2007). The system also presents a wide nebulosity in optical atomic lines, which extends about 2′. The optical nebulosity would be expanding at about 50 km s^{-1} (e.g., Hollis et al. 1999) in the plane of the binary orbit, though occupying a region of about 1000-times larger.

Usually, the nebulae around symbiotic stars are poor in molecular line emission (e.g., Bujarrabal & Pardo 2007; Ivison et al. 1995). R Aqr is a symbiotic system presenting the best studied molecular spectrum. Its SiO maser intensity is normal, compared to that of standard Mira stars (Bujarrabal et al. 1987, Pardo et al. 2004), and has been relatively well studied, including detailed high-resolution mapping using VLBI techniques. The SiO maser probably originates in the close surroundings of the Mira-type variable, forming the typical ring of spots (e.g., Boboltz et al. 1997, Hollis et al. 1990). On the other hand, the H_2O maser emission from this object is weak (Ivison et al. 1995); the existing maps are not very accurate, but they tend to show an elongation in the direction of the jet (Ivison et al. 1998). OH (maser) and CO (thermal) lines are very weak and only tentative detections have been published (Ivison et al. 1994; Groenewegen et al. 1999).

In this paper, we present phase-referenced maps of two SiO maser transition: $v = 1$ $J = 1$–0 and $v = 2$ $J = 1$–0 on 2004 December and 2005 December. In section 2 we describe observations and results. We discuss the abusolute propepr motion and SiO maser distribution in sections 3 and 4. Conclusions are given in section 5.

2. Observations and Results

2.1. Observations and Data Reductions

The 43 GHz VLBI observations were made on 2004 December 23 (2004.98) and 2005 December 24 (2005.98), using 4 antennas of VERA. The SiO masers around R Aqr (Hipparcos coordinates: $\alpha_{\rm J2000} = 23^{\rm h}43^{\rm m}49\overset{\rm s}{.}4616$, $\delta_{\rm J2000} = -15^{\rm d}17'04\overset{''}{.}202$) and the extragalactic source J2348−1631 ($\alpha_{\rm J2000} = 23^{\rm h}48^{\rm m}02\overset{\rm s}{.}608532$, $\delta_{\rm J2000} = -16^{\rm d}31'12\overset{''}{.}02226$) were observed simultaneously using the two receivers in each telescope. The optical phases of our observations were $\phi = 0.25$ and $\phi = 0.19$, for epochs 2004.98 and 2005.98, respectively, based on data from the General Catalogue of Variable Stars, and in agreement with contemporary optical light curves (kindly provided by the AAVSO). Note that both epochs are quite close to those of the expected emission maxima ($\phi \sim 0.10$–0.15, see Pardo et al. 2004), in which relatively rich maser structures should appear.

Each observation lasted ~ 7 hr, including scans of the targets and a calibrator (3C454.3). The data were recorded onto magnetic tapes at a rate of 1024 Mbps, providing a total bandwidth of 256 MHz, in which two IF channels were assigned to the $v = 1$ $J = 1$–0 and $v = 2$ $J = 1$–0 SiO maser transitions toward R Aqr; other 14 IF channels were assigned to the position reference source J2348–1631. The instrumental phase difference between the two receivers was measured in real time during the observations, by correlating random signals from artificial noise sources injected onto the receivers (Honma et al. 2008a).

Data reduction and the identification of maser spots were made using the NRAO AIPS packages. We followed two steps to obtain the relative positions of all maser spots to the tracking center. First of all, an interactive self-calibration and imaging procedure was performed, in order to map a simple strong reference spectral feature in each transition, and then to detect weak spots. The resulting phase solutions were applied to all channels, and we obtained the positions of maser spots relative to the reference channel using the AIPS task SAD. A typical size of the synthesized beam was 0.8×0.5 milliarcseconds (mas) with PA $\sim -20°$.

Next, a fringe fitting was performed using the AIPS task FRING on the reference source, and the solutions were applied to the target source. Then, amplitude and a bandpass calibrations were made for the target and the reference source independently. Additionally, correction table of the instrumental phase difference described above was adopted. Because the a priori delay model applied in the correlation processing was not sufficiently accurate for precise astrometry, we calibrated the visibility phase using the most accurate delay model, based on recent achievements of geodynamics in the analysis. In this model, we calibrated the fluctuation of the visibility phase caused by Earth's atmosphere, based on GPS measurements of the atmospheric zenith delay due to the tropospheric water vapor (Honma et al. 2008b). We then obtained the positions of some simple and bright maser spots relative to the tracking

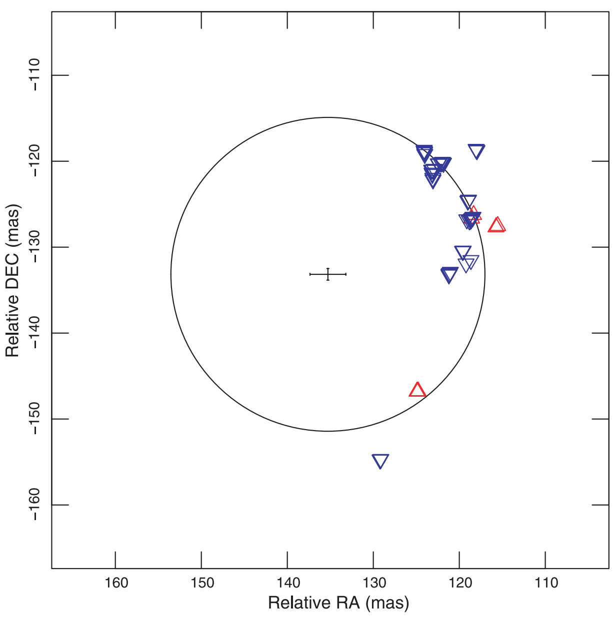

Fig. 1. Distribution of SiO masers around R Aqr on 2004.98. The red triangles (pointing upwards) represent the distribution of the $v = 1$ $J = 1$–0 transition and the blue triangles (pointing downwards) represent the spots of the $v = 2$ $J = 1$–0 transition. The solid circle and the central cross represent the result of a circular fitting of the positions of all maser spots.

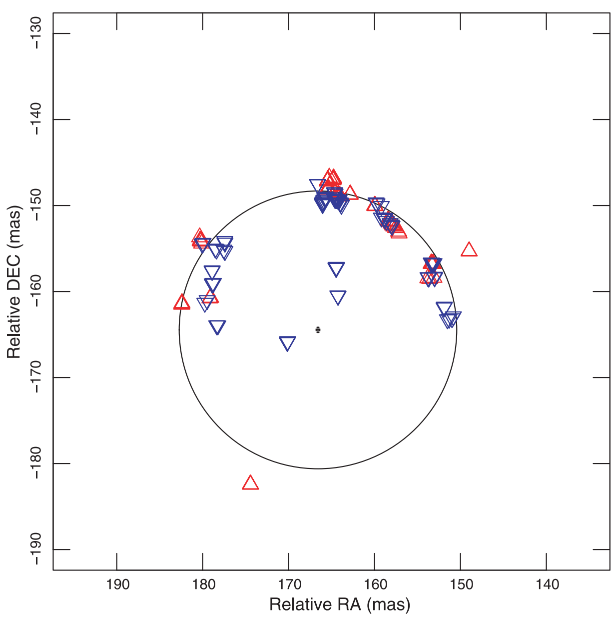

Fig. 2. Same as figure 1, on 2005.98. The solid circle and the cross represent the result of a circular fitting of the positions of all maser spots.

center using the AIPS task JMFIT. Finally, we compared the positions of the identified maser spots of the self-calibrated images, and the phase-referenced images, and calculated the offsets to be applied to the former images to determine the positions of all maser spots relative to the tracking center.

2.2. *Results*

Figures 1 and 2 show the distributions of the $v = 1$ $J = 1$–0 and $v = 2$ $J = 1$–0 transitions relative to the tracking center. The SiO maser spots seem to be distributed on a ring-like structure. Reid and Menten (2007) have shown that such maser rings are centered on the star. We obtained the stellar positions by a circular fitting of the spot distribution, while introducing no weighting. Because of a small number of maser spots of the $v = 1$ $J = 1$–0 transition in 2004.98, we used both maser transitions together to obtain the stellar positions. The obtained parameters are summarized in table 1. The uncertainties listed in table 1 are formal errors derived from the circular fitting procedure. We discuss the proper motions in section 3, and the channel maps of both epochs in section 4.

Table 1. Measured positions of the star.*

Epoch	RA [mas]	Dec [mas]
2004.98	135.3 (2.09)	−133.2 (0.68)
2005.98	166.6 (0.21)	−164.5 (0.30)

* Formal uncertainties are given between brackets.

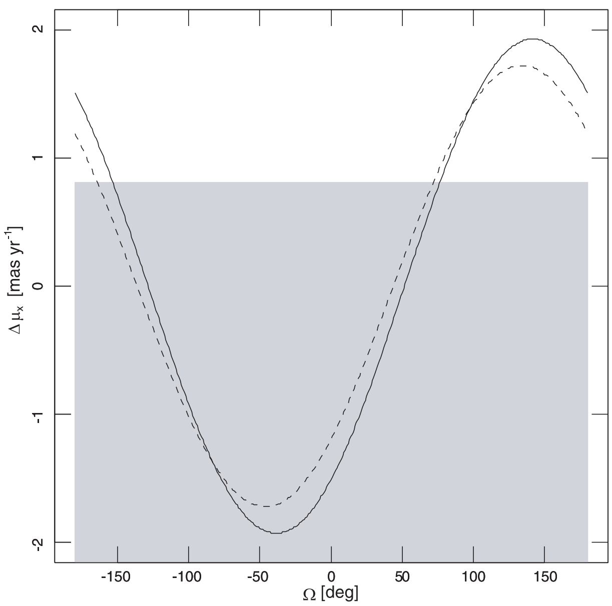

Fig. 3. Difference of the proper motion between 2004.98 and 1991.25 for RA, depending on the possible values of Ω. The grey region represents the values allowed by observations. The solid and dashed lines show the cases of clockwise rotation and counter-clockwise rotation, respectively.

3. Proper motions of R Aqr from SiO maser astrometry

In this section, we discuss the absolute proper motions. We obtained two absolute positions on the same date in each year; thus, the effect of parallax can be ignored as well as the proper motions obtained by connecting these two positions.

The proper motion obtained from our observations is $(\mu_x, \mu_y) = (31.24 \pm 2.09,\ -31.24 \pm 0.74)$ [mas yr^{-1}], which is very similar to previous results obtained by Hipparcos, $(32.98 \pm 1.46, -32.61 \pm 1.13)$ [mas yr^{-1}]. The differences are $(-1.74 \pm 2.55, 1.37 \pm 1.35)$.

As mentioned in section 1, this object is known to be a symbiotic system, but the orbital elements are not well known. In this section we will try to improve them with our VERA data.

McIntosh and Rustan (2007) extracted the orbital parameters of the binary star system from measurements of the radial velocity of the long-period variable, but they could not obtain the angle from the RA axis to the line of nodes, Ω, because this value does not affect the the radial velocity of the star. We calculated the expected differences of the proper-motion values measured in 1991.25 (when the Hipparcos observations were made) and in 2004.98 for the possible values of Ω, from −180° to 180°. Such expectations were compared with the observational results (figures 3 and 4). We can thus extract the allowed ranges for Ω, which are found to be $-39° < \Omega < 77°$, for clockwise orbiting, and $-46° < \Omega < 73°$ for counter-clockwise. Because of these very wide ranges, even if only 1-σ errors are considered, our results on this topic cannot further constrain the orbit. We summarize the obtained orbital parameters in table 2.

Hollis, Pedelty, and Lyon (1997) also deduced a set of values of the orbital parameters, $(P, e, T_0, i, \Omega, \omega, M_{\rm s+LPV}) = (44\,{\rm yr},\ 0.8,\ 1974.14,\ 70°,\ \sim 0°,\ 90°,\ 3M_\odot)$, which are very different from those by McIntosh and Rustan (2007). Adopting

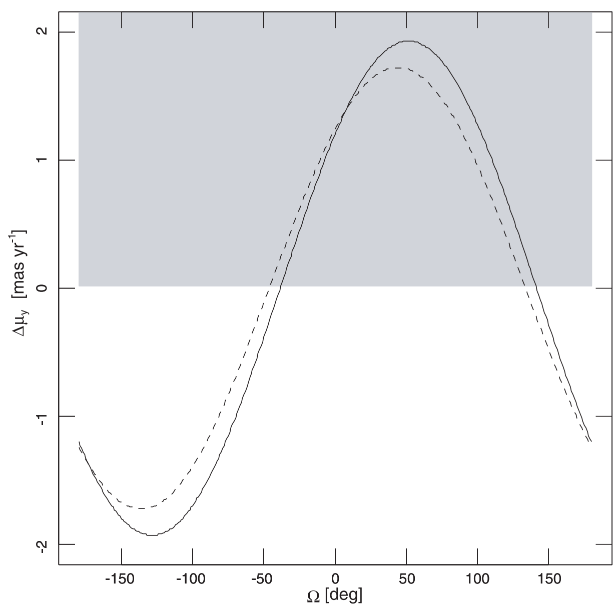

Fig. 4. Same as figure 3 for Dec.

Table 2. The derived orbital elements for R Aqr.*

Element	Value	Clockwise	Counter-clockwise
P (yr)	34.6 ± 1.2	⋯	⋯
T_0	1980.3 ± 0.8	⋯	⋯
$K_{\rm LPV}$ (km s^{-1})	3.5 ± 0.6	⋯	⋯
e	0.52 ± 0.8	⋯	⋯
$a \sin i$ (AU)	3.5 ± 0.4	⋯	⋯
ω (deg)	110.7 ± 18.4	⋯	⋯
Ω (deg)	⋯	$-39 < \Omega < 77$	$-46 < \Omega < 73$

* Based on our data and the previous values by McIntosh and Rustan (2007).

Hollis et al's values, the expected difference of the proper motion ($\Delta\mu_x, \Delta\mu_y$) is (0.17, 0.94) [mas yr^{-1}] for counter-clockwise rotation, and (−0.17, 0.94) [mas yr^{-1}] for clockwise rotation. These predictions are also consistent with our proper-motion measurements within the errors. Therefore, we cannot conclude about which set of orbital parameters is more reliable. Again, we note that these proper-motion measurements can hardly discriminate between sets of orbital parameters showing significant differences.

We also note that a newly revised Hipparcos astrometric catalogue, using new data reductions, have been reported (Knapp et al. 2003; van Leeuwen 2007). From these, we find that the Hipparcos positional errors might be larger than previously reported. If the Hipparcos positional errors are more than twice those previously assumed, the differences in the proper motions that we have obtained will be too uncertain to make any conclusion about the orbital elements.

For our data to be useful to estimate the value of the angle Ω within 10 degrees precision (assuming the other parameters by McIntosh & Rustan 2007), we should be able to measure the differences of the proper motions for observations obtained between 2004.98 and 2014.98 within 1 mas accuracy. If we use observations performed between 2005.98 and 2008.98, we must obtain differences of the proper motions within 0.2 mas precision to estimate the value of Ω with the same accuracy as mentioned above. We have made more observations so as to improve the positional errors, and plan to continue observing this source in the near future.

4. Relative Positions of the $v = 1$ and $v = 2$ $J = 1$–0 Maser Spots

It is known that the $v = 1$ and $v = 2$ $J = 1$–0 masers form rings of spots at a few stellar radii from the star, the $v = 2$ $J =$ 1–0 rings being slightly smaller (see Cotton et al. 2006, and references therein). Since Desmurs et al. (2000), it is known that the $v = 1$ and $v = 2$ $J = 1$–0 maser spots often occupy nearby regions, but are rarely coincident.

We can see in figures 5 and 6 the spatial distribution of the SiO maser spots, as a function of their LSR velocity, for both observed epochs (2004 December and 2005 December), and both observed transitions ($v = 1$ $J = 1$–0 and $v = 2$ $J = 1$–0). Our observations of R Aqr follow the trends characteristic of standard AGB stars, mentioned in the previous paragraph.

Previous VLBI mapping of SiO emission from R Aqr by Hollis et al. (2000, 2001) and Cotton et al. (2004, 2006) have led these authors to propose that the inner circumstellar envelope of R Aqr may be in Keplerian rotation. However, the different observations in these papers suggest quite different rotation axes and in some cases the velocity field does not indicate any rotation. In our two observations, the distribution and velocities of the maser spots do not agree with the Keplerian rotation. In a forthcoming paper, we will present further observations of R Aqr in several epochs (still under analysis) and, based on a large number of data, the evolution of the spatial and velocity distribution of the maser spots will be discussed in detail. In that paper we will also compare our velocity centroids with the data on velocity time variations by McIntosh and Rustan (2007). We note that, both in 2004.98 and 2005.98, the SiO emission in our data is relatively redshifted, in agreement with the recent trend to less negative velocity values given by those authors.

4.1. *$v = 1$ and $v = 2$ $J = 1$–0 Masers: Relative Spatial and Kinematical Distributions*

Thanks to the very good astrometry performed by VERA, the absolute coordinates of the $v = 1$ and $v = 2$ spots in our maps have been very accurately measured.

In 2004, ~ 41 spots were detected in the $v = 2$ $J = 1$–0 transition and 7 spots were identified in the $v = 1$ line. Of these spots, only one coincides in both position (within two thirds of the beam size) and velocity for the two lines. In 2005, the number of spots was higher; a total of 75 spots were identified in the $v = 2$ $J = 1$–0 maser and 66 spots appear in $v = 1$ $J =$ 1–0. Of them, 16 are coincident in position and velocity for both lines, with the above criterion. If we chose the condition for coincidence to be closer than $1/3$ of the beam, we have, respectively for both epochs, 1 and 11 spots in common.

We recall that the high astrometric accuracy of VERA guarantees that these coincidences are reliable.

As we have seen, typically, about $1/6$ of the spots emitting in $v = 1$ $J = 1$–0 also appear in the other line, and about $1/10$ (between $1/5$ and $1/40$) of the spots detected in the $v = 2$ $J =$ 1–0 maser are also found in $v = 1$ $J = 1$–0. Therefore, we accurately confirm the conclusion by Desmurs et al. (2000). Although both maser lines come from similar circumstellar regions, their spots are only coincident in a small fraction of the cases. Often, the spots of both lines are very nearby, but not coincident, separated by 1–2 mas.

We note that relatively complete rings of spots were detected in our 2005.98 observation. In 2004 December, however, most of the spots were aligned in the west part of the envelope, for both the $v = 1$ and $v = 2$ lines. In both epochs, the $v = 2$ $J =$ 1–0 maser presents significantly more spots than the $v = 1$ $J =$ 1–0 one, but both lines present similar overall distributions.

4.2. *Comparison with Theoretical Model Predictions*

We have addressed the question of the coincidence of spots emitting in the $v = 1$ and $v = 2$ $J = 1$–0 masers from very accurate astrometric measurements, obtaining a quantitative estimate of the percentage of coincidences for the first time.

The spot coincidence had been used as an argument for favoring radiative or collisional pumping mechanisms; the lack of systematic coincidences tends to favor radiative pumping

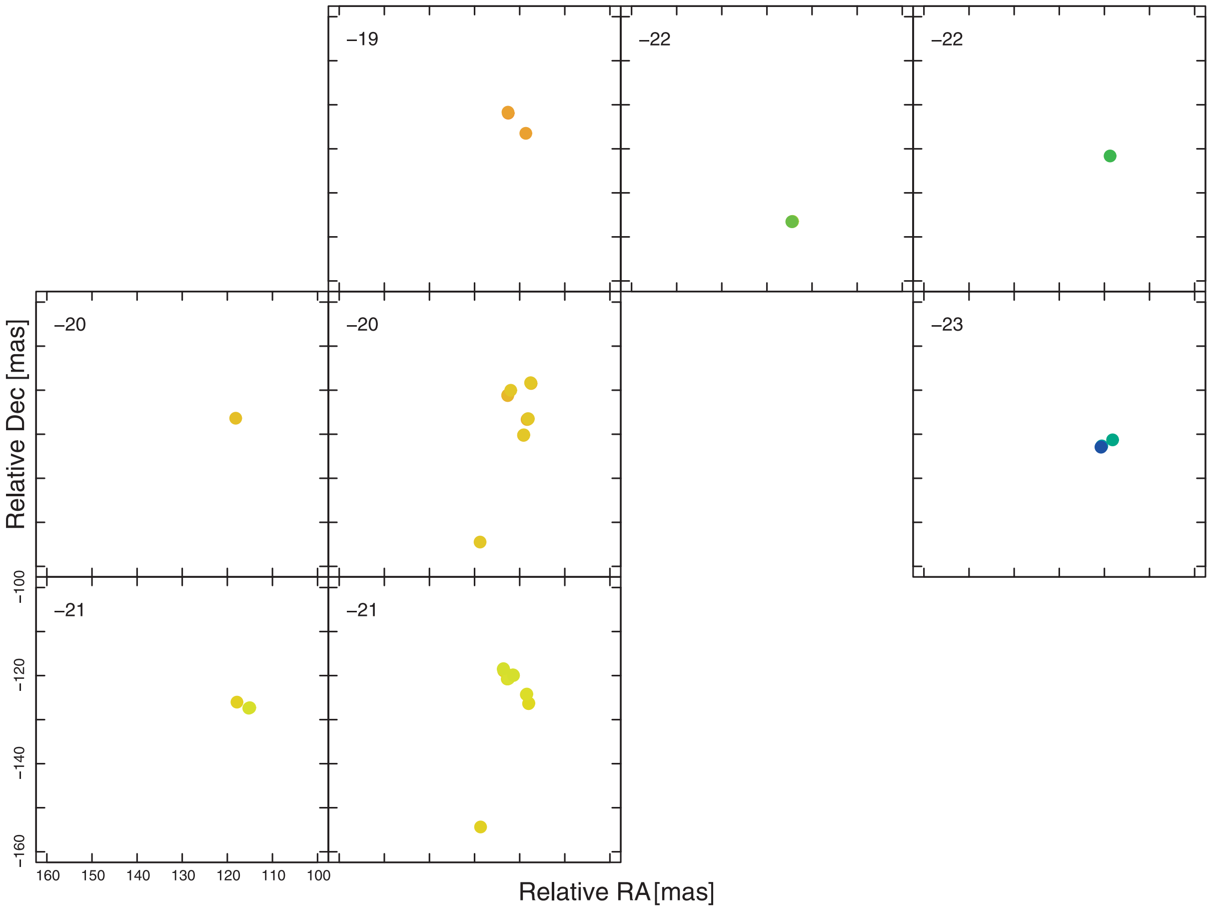

Fig. 5. Velocity channel maps of the two transitions observed on 2004 December 23. The odd columns show channel maps of the $v = 1$ $J = 1$–0 line, and even columns show channel maps of $v = 2$ $J = 1$–0. LSR velocities are indicated in the upper-left corner of the panels.

(see details in the extensive discussion by Desmurs et al. 2000).

In the standard versions of both pumping schemes (see e.g., Bujarrabal & Nguyen-Q-Rieu 1981; Lockett & Elitzur 1992), inversions of the $v = 1$ and $v = 2$ rotational transitions appear under quite different conditions: the $v = 1$ state is at 1800 K over the ground, while the $v = 2$ one is at 3600 K, so different (always higher) excitations would be required. Therefore, the conditions under which both masers can coexist are rare in both models. In the radiative model, the coincidence is somewhat less probable than for the collisional pumping, which has led to a long-lasting discussion concerning the consequences on theoretical modeling of the possible systematic coincidence of $v = 1$ and $v = 2$ $J = 1$–0 spots. Both pumping mechanisms predict that masers of rotational transitions within the same vibrational state ($J = 1$–0, $J = 2$–1, etc) must be strongly coupled, and should appear at practically the same points.

The discussion on this topic dramatically changed when the first comparisons between the $v = 1$ $J = 1$–0 and $J = 2$–1 maser distributions were performed (Soria-Ruiz et al. 2004, 2005, 2007). The $v = 1$ $J = 2$–1 maser spots systematically occupy a ring with a significantly larger radius than that of $v = 1$ $J = 1$–0, and both spot distributions are completely unrelated.

Soria-Ruiz et al. (2004) interpreted these results by invoking line overlap between the $v = 1, J = 0 \rightarrow v = 2, J = 1$ rovibrational transitions of SiO and the $\nu_2 = 0,12_{7,5} \rightarrow \nu_2 = 1,11_{6,6}$ rovibrational line of H_2O (see also Olofsson et al. 1981; Bujarrabal et al. 1996). Their calculations indicate that this line overlap reinforces the $v = 1,2$ $J = 1$–0 masers; a quenching of the (otherwise intense) $v = 2$ $J = 2$–1 maser is also produced, in agreement with observations. A very important consequence is that, following Soria-Ruiz et al. (2004), the overlap introduces a strong coupling between $v = 1,2$ $J = 1$–0 masers, that now are predicted to require very similar conditions to be intense, while the $v = 1$ $J = 2$–1 maser is less affected by this phenomenon, and now shows practically no relation with them. The calculations by these authors are in agreement, at least qualitatively, with all existing observations. In our opinion, it is not possible to understand the high-resolution maps of SiO masers without taking into account those theoretical considerations on the effects of line overlap.

Our maps very accurately confirm previous results on the $v = 1,2$ $J = 1$–0 maser distributions. The spots of both transitions are placed in similar regions, but are rarely coincident. The results of radiative pumping models including line overlap, as proposed by Soria-Ruiz et al. (2004), are compatible with

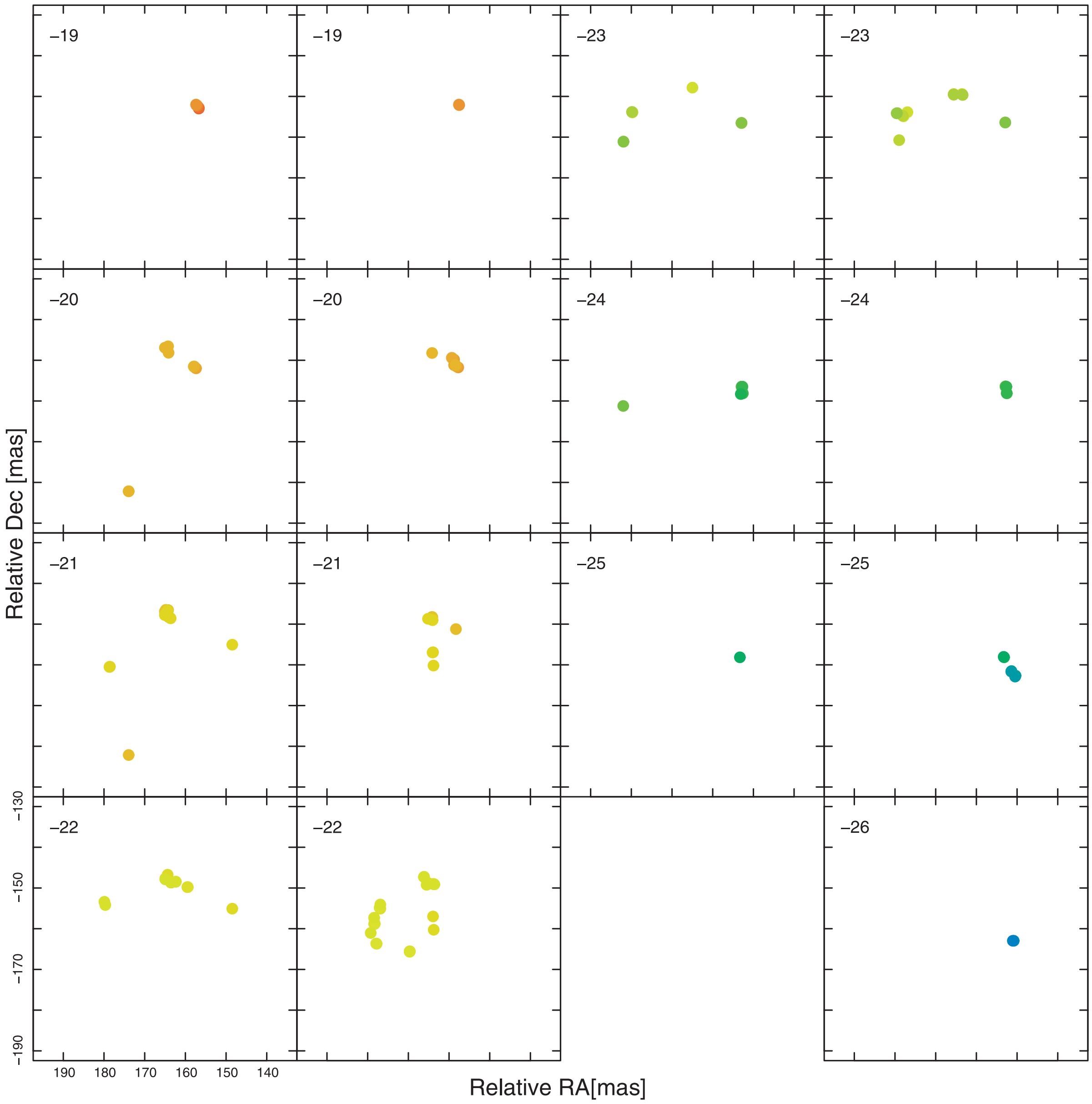

Fig. 6. Same as figure 5, for epoch 2005.98.

these observational data. However, we still lack specific theoretical studies on the probability of detecting, in both $v = 1$ and $v = 2$ $J = 1$–0, spots with very high brightness. Further theoretical studies in this direction are thus required.

5. Conclusions

We present VERA mapping of the $v = 1$ and $v = 2$, $J = 1$–0 SiO maser lines in the symbiotic stellar system R Aqr, which contains a Mira-type star. Two epochs were observed, 2004.98 and 2005.98. Very accurate astrometry has been obtained, thanks to the VERA double-beam technique. We have further estimated the position of the centroid of the SiO emission from the fitting of a circular distribution to the maser spot positions; this centroid is supposed to be coincident with the Mira star. We also measured the proper motions for the centroids. The uncertainties of these parameters were also carefully estimated.

We have tried to improve the determination of the orbital elements of the binary by comparing the VERA coordinates and the proper motions with values obtained by Hipparcos in 1991.25. In principle, such a procedure should discriminate between the different orbits that are compatible with previous data. However, the uncertainties in the measurements are still too large, and our results are not conclusive. Further VERA observations are planned in order to better address this problem.

Our data also allow an accurate comparison of the relative positions of the spots of both $J = 1$–0 $v = 1$ and $v = 2$ masers. We find that, for each epoch, both lines present quite similar distributions. However, the spots are rarely coincident. Depending on the considered line and epoch, the relative number of coincident spots ranges between approximately 3% and 20%. The lack of any systematic coincidence favors radiative pumping schemes, instead of the collisional mechanisms (e.g., Desmurs et al. 2000) for standard versions of the models. However, models including additional line-overlap effects, see Soria-Ruiz et al. (2004, 2006), are required to explain the relative positioning of the spots of the different maser lines (not only those observed by us). Such models are not yet capable of fully addressing the issue of spatial coincidence. We think that further theoretical efforts are necessary on this topic, while discussing in detail the effects of line overlap on the line inversion and the possible coincidence of very intense, saturated maser lines.

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