THE ASTROPHYSICAL JOURNAL, 423:L143–L146, 1994 March 10

THE SPATIAL SIZE OF THE SiO MASERS IN R LEONIS DERIVED FROM LUNAR OCCULTATIONS

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Received 1993 October 12; accepted 1993 December 20

ABSTRACT

We have observed the $v = 1$ $J = 2 \rightarrow 1$ SiO maser transition in the late M-type star R Leo with the 30 m IRAM radio telescope during a lunar occultation of this source. Significant power fluctuations (Fresnel fringes) were recorded with a signal-to-noise ratio of 10–30 at immersion and emersion of the source over the full velocity range of the maser emission. The data sampling rate was of 50 ms which provides an angular resolution of $\simeq 25$ mas for the velocities of the strong masers and of $\simeq 50$ mas in the line wings. The restored brightness distribution is consistent with a source of 60 mas in diameter (1.1×10^{14} cm for a distance of 120 pc which corresponds to a diameter of 4 stellar radii). The observed velocity field for the gas between 1 and 2 stellar radii could fit a rotating structure (disk/ring/spherical shell). The velocity field derived for the line wings suggests a bipolar mass loss from the star, extending at least over 8 stellar radii. High sensitivity observations of several SiO maser transitions in R Leo show emission at velocities larger than the expanding velocity of the external molecular envelope. These maser clumps are probably arising from the bipolar outflow observed in the lunar occultations. This is the first time that lunar occultations at millimeter wavelengths provide the maximum angular resolution information contained in the Fresnel fringes.

Subject headings: occultations — masers — radio lines: stars — stars: individual (R Leonis)

1. INTRODUCTION

SiO maser emission from the circumstellar envelopes of oxygen-rich evolved stars can be used to study the physical conditions close to the stellar surface. The modeling of the pumping mechanisms for the rotational transitions of the different vibrational states of SiO can provide useful constraints on the volume density, molecular abundance, velocity field, and geometry of these regions (see, e.g., Cernicharo & Bujarrabal 1992; Cernicharo, Bujarrabal, & Santarén 1993). Unfortunately, single-dish and connected interferometric observations lack the angular resolution necessary to resolve the masers, which appear as pointlike sources even for the largest radio telescopes. VLBI observations seem to indicate that the maser-emitting regions are very clumpy and that these clumps extend over several stellar radii (McIntosh 1987; McIntosh et al. 1989; Colomer et al. 1992). However, VLBI observations cannot provide the large-scale structure of the emitting regions. It appears that the ideal instrument for the study of the SiO masers would be an interferometer with baselines covering the range from a few to several thousands of kilometers.

A classical way to get high angular resolution and full beam synthesis with a single-dish telescope of moderate size is via lunar occultations. This observing technique provides the angular resolution of a single line antenna several kilometers long (Hazard 1976). However, lunar occultations at millimeter wavelengths have been used so far to improve the angular resolution of the observing telescope by only a factor 2–5 (Schloerb & Scoville 1980; Snell & Schloerb 1985). No single millimeter-wavelength antenna was sensitive enough, to our knowledge, to observe the Fresnel fringes produced by the Moon limb as the source was occulted. In this *Letter*, we report the observation with the IRAM 30 m radio telescope of the $v = 1$ $J = 2 \rightarrow 1$ SiO maser line during an occultation (and reappearance) of R Leo by the Moon. The superior sensitivity of the instrument allowed to get a good sampling of the Fresnel fringes and to detect them. The restored brightness distributions have a resolution corresponding to that provided by a line antenna 30 km long, i.e., 25 mas.

2. OBSERVATIONS AND RESULTS

Three occultations of R Leo by the Moon were expected in 1990 at Pico Veleta. Observations during the first event in 1990 May were successful, and the results are presented in this *Letter*. The second event in 1990 June was lost due to bad weather and the third event in 1990 August was also lost due to strong anomalous refraction. The two masing $J = 3 \rightarrow 2$ and $J = 2 \rightarrow 1$ transitions of the first vibrational state of SiO were observed simultaneously with the IRAM 30 m radio telescope. The spectrometers used were a 2×128 channels 100 kHz filterbank and a 2×256 channels 1 MHz filterbank. Another filterbank backend with 512×1 MHz channels was also available. The SSB receiver temperature was 130 and 110 K for the 3 mm and the 2 mm receivers respectively. The sky opacity at the observed frequencies was $\simeq 0.1$. The total main beam system temperature, including contribution by the Moon was $\simeq 600$ K.

The feasibility of this experiment is conditioned by the signal-to-noise ratio one can obtain from very short integration times. The Fresnel zone size at 3 mm wavelengths is $\simeq 0\farcs4$, which roughly corresponds to the motion of the Moon on the sky in 1 s (see Hazard 1976). Consequently, the fringe rate is

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roughly of one fringe per second, and the integration time is limited by the final angular resolution we intended to reach, which depends, among other parameters, on the observational sampling of the diffraction pattern produced by the Moon limb. The adopted integration time during immersion and emersion of the source was 50 ms. Because of the very high data acquisition rate, special programs were written to allow a fast reading of $2 \times 512 \times 256$ channels every 50 ms. The standard observing programs of the observatory were used only to correct for antenna pointing errors, to focus, and to point the telescope on the Moon limb at the positions where the occultation and reapparition were expected. The programs were checked during an occultation by the Moon of IRC +10216 in 1989 and proved to work satisfactorily. The occultation of R Leo in 1990 May was nearly central, i.e., the occultation and reappearance positions were on the line described by the Moon center in its apparent path on the sky (movement of the Moon in a 33° paralactic angle and occultation angles of 5°.5 relative to this direction).

At millimeter wavelengths, the variation of the received power due to the contribution from the Moon can be as high as the receiver noise temperature. Consequently, the baseline quality can be considerably degraded due to power unbalance between ON and OFF source integration. In order to get a total power as constant as possible during the occultation and the reapparition, the telescope was tracking the Moon limb at the point where the occultation and the reappearance were expected. Even with this method, small motions of the telescope beam across the Moon limb produce significant changes in the received power. In order to get a good power balance between the ONs and the OFFs, we observed at different positions perpendicular to the Moon limb during 2 minutes each. These positions, $\pm 15''$, $\pm 10''$, $\pm 5''$, and $0''$ relative to the occultation point at the Moon limb, were our reference OFFs spectra. The observed total power on each ON was used to interpolate between the OFFs to produce a reference spectrum with the same power as the ON. The resulting baselines are very flat, and only a linear baseline has been removed in the final data analysis (see Fig. 1). The measured rms noise in each spectrum was 8.5 and 2.7 K for the 100 kHz and 1 MHz filters, respectively. Since the telescope beam (27″ HPBW at the frequency of the $J = 2 \rightarrow 1$ $v = 1$ SiO transition) was pointed on the Moon limb, the Fresnel fringes were observed with a varying gain as the source was approaching the occultation point (this variation is negligible for the first Fresnel fringes which are observed close to the electrical axis of the telescope). Consequently, the observed diffraction pattern was deconvolved with a Gaussian corresponding to the telescope beam. The final occultation and reapparition diffraction curves are shown in Figure 2 for several velocities.

The adopted restoration method was that proposed by Scheuer (1962). The difference between the calculated and observed immersion and emersion times was −0.7 and 0.8 s (i.e., $\simeq -0''.3$ and $0''.4$, respectively), which is probably due to the Moon limb irregularities and to systematic errors of the Moon ephemerides (for more details, see Hazard 1976). We also used a model-fitting procedure to restore the brightness distribution of the SiO masers. This technique provides a better signal-to-noise ratio if some constraints on the signal can be imposed. The spatial distribution of the SiO brightness at each velocity was assumed to be consisted of a series of step functions with an elementary resolution of 6 mas and variable intensity. This spatial distribution was convolved with the dif-

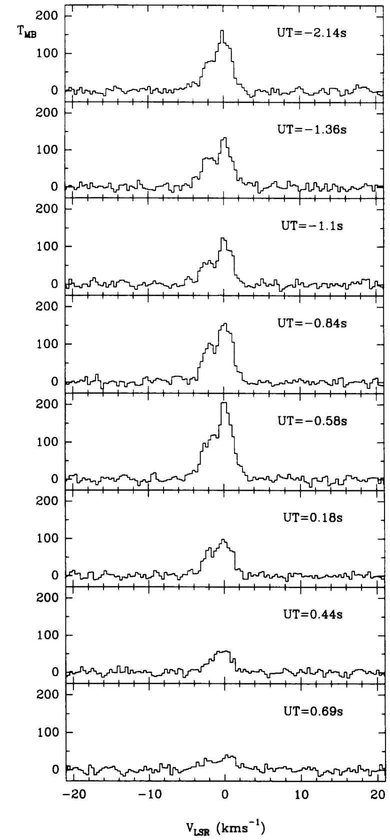

FIG. 1.—Observed SiO $v = 1$ $J = 2$–1 emission during the occultation of R Leo by the Moon in 1990 May. Observing time is 50 ms per spectrum. Note the variations in the line intensity as the source is occulted by the Moon. The spectral resolution is 0.3 km s^{-1}. The X-axis is the velocity, in km s^{-1}, and the Y-axis is the main beam antenna temperature in kelvins. The numbers in the different panels indicate the Universal Time with respect to the expected occultation time of R Leo by the Moon.

fraction pattern of a pointlike source. Intensities for each elemental step function were derived from a least-squares fit assuming that the signal could be only positive. The results of both procedures agree very well. For moderate to low maser emission, the fitting technique improves the signal-to-noise ratio considerably when compared to the Scheuer method. Numerical simulations with several types of spatial distributions and with a signal-to-noise ratio similar to that observed during the occultation indicated that the angular resolution we could achieve was of 25 mas for the velocities of strong maser emission and of 50 mas in the line wings. Figure 3 shows a position-velocity diagram containing all the points where emission was observed independently of their intensity (all the restored brightness distributions have been normalized to unity). The signal-to-noise ratio is $\simeq$20–30 in the velocity range −3 to 2 km s^{-1} and of the order of 5–10 in the line wings. Positions are relative to the occultation and reappearance times of the velocity channel at 0.1 km s^{-1}. This figure shows the velocity field in the innermost regions of the molecular envelope.

3. DISCUSSION

Figure 3 shows that the bulk of the SiO $J = 2 \rightarrow 1$ $v = 1$ maser emission arises from a region 60 mas wide and with a clear spatial separation at extreme velocities. For each velocity the restored brightness distributions has a half-power intensity

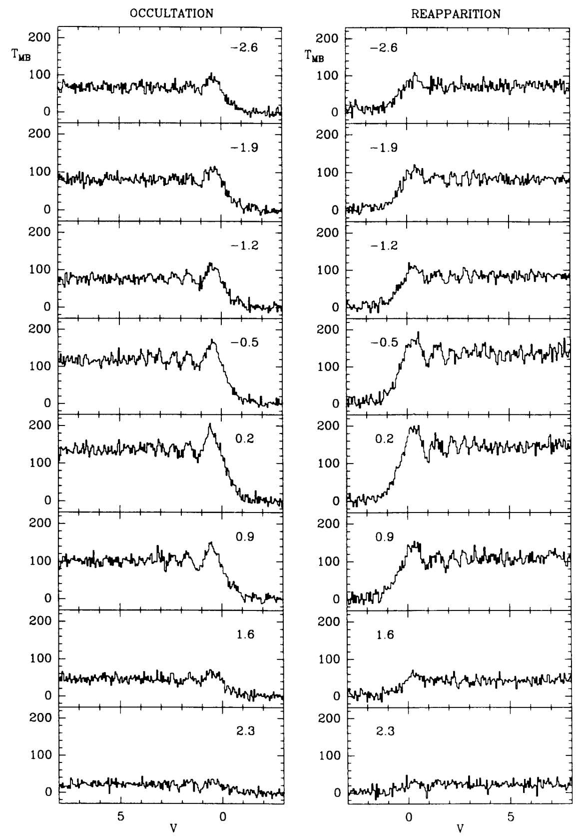

FIG. 2.—Observed diffraction pattern in the emission of the SiO $v = 1$ $J = 2$–1 line at several velocities during the occultation and reapparance of R Leo by the Moon. The X-axis is in Fresnel units ($1v \simeq 0\rlap{.}''4$), and the Y-axis is the main beam antenna temperature. The numbers in each panel correspond to the velocity of the emission in km s^{-1}.

size of 40–60 mas which is similar to the derived size of the emitting region and 2 times larger than the expected half-power size derived from the numerical simulations quoted above. The difference in velocity between the emission at the positions +30 mas and −30 mas is 4 km s^{-1}. The picture shown in this figure suggests a rotation of the gas where the maser emission is produced. However, due to our limited angular resolution, we cannot exclude that the emission is arising from three different clumps at −2.4, 0, and 1.6 km s^{-1}. Although the final achieved resolution is 25 mas, each individual velocity channel shows a systematic change in its position centroid, which is very suggestive of rotation and excludes a general expansion of the region as origin of the observed velocity field. Unfortunately, the lack of angular resolution in the direction perpendicular to the Moon path on the sky precludes any determination of the true geometry of the emitting region (disk/sphere/spherical shell). Assuming a distance of 120 ± 15 pc (Gatewood 1992; see also Celis 1984) the observed angular size corresponds to a linear dimension of 1.1×10^{14} cm. The stellar radius has been derived from the same lunar occultation event (1990 May) by Giacomo et al. (1991) at 2.16 μm. They obtained a diameter of 33 ± 1.3 mas. With this value the strong SiO maser emission exends over 4 stellar radii. VLBI observations of R Leo in the $J = 1 \rightarrow 0$ $v = 1$ line of SiO by Lane (1984) indicate that the maser spots extend over 60 mas, which is compatible with the total size we derive. However, the $J = 2 \rightarrow 1$ and $J = 1 \rightarrow 0$ maser lines have many qualitative differences (McIntosh 1987), and the agreement can be purely fortuitous. Subsequent observations of the same source in the $J = 1 \rightarrow 0$ $v = 1$ line in 1985 by McIntosh (1987) indicate a size for this emission of 35 mas. However, the spectral profile of this line was unusual, with emission at velocities between 0 and 10 km s^{-1} rather than those shown in Figure 1 which are more typical for this source. Recently, Colomer et al. (1992) have observed R Leo in the $v = 1 \rightarrow 0$ line of SiO with baselines up to 750 km and detected structure at velocities of −1.9 and 2.9 km s^{-1} with estimated sizes of 1 and 1.5 mas, respectively. Unfortunately, they do not provide the angular separation between these two spectral features and no structure in the velocity region of maximum maser emission was reported. If we assume that the masers detected in the lunar occultation have a spherical symmetry with a radius of 30 mas, then the observed single disk brightness temperature of 150 K (700 Jy) corresponds to a true brightness temperature average over the source of 4.4×10^7 K.

At extreme velocities, $v > 2.0$ and $v < -3.5$ km s^{-1}, Figure 3 shows a velocity behavior similar to that expected from a bipolar outflow. Positive velocities are detected at positive offsets (between 160 and 30 mas) before the Moon limb reaches the position of strong maser emission. Once this region has been occulted, only extreme negative velocities are observed extending between −30 and −160 mas. These velocities, which correspond to the line wings of the maser emission (see Fig. 1), are not detected in the VLBI experiments because of lack of sensitivity. It is most likely that SiO maser emission at

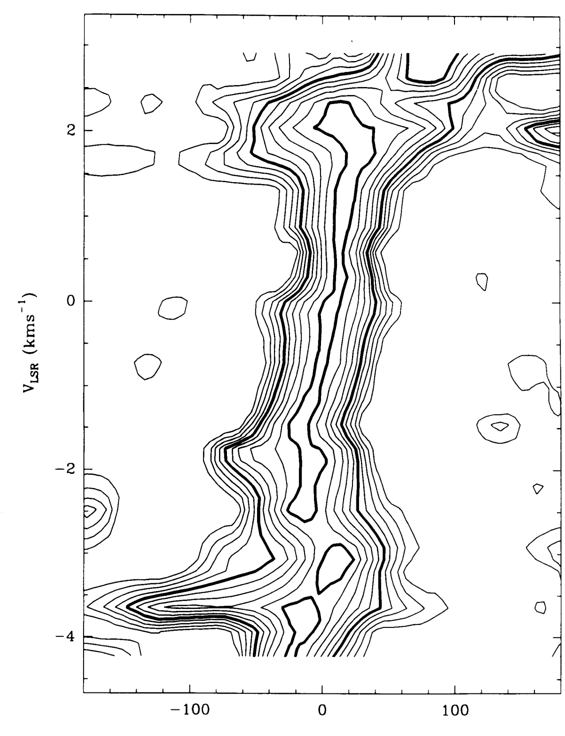

FIG. 3.—Velocity field around R Leo derived from the data of Fig. 2. All the spatial brightness distributions derived for all the velocities were normalized to unity. This figure shows the spatial distribution of all the velocities for which SiO maser emission is found. The X-axis is the position in mas along the Moon path on the sky. The Y-axis is the velocity in km s^{-1}. First contour and step are 0.1; thick contours represent the half-power and 98% levels of these normalized brightness distributions.

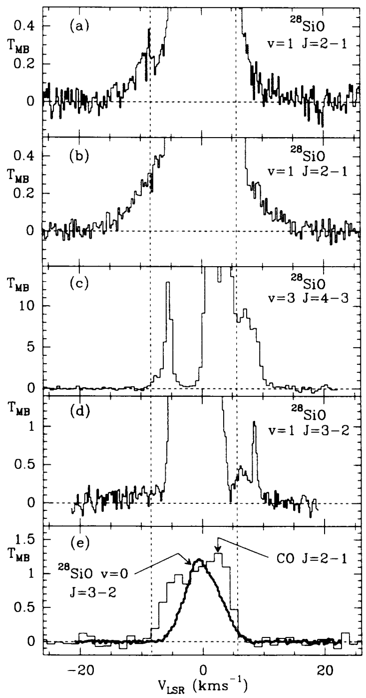

FIG. 4.—Observed single-dish spectra in 1992 June and November toward R Leo in the transitions of SiO $v = 1$ $J = 2 \rightarrow 1$ (*a*) 1992 June and (*b*) 1992 November, $v = 1$ $J = 3 \rightarrow 2$ (*c*) and $v = 3$ $J = 4 \rightarrow 3$ (*d*), $v = 0$ $J = 3 \rightarrow 2$ (*e*) (*thick line*) and in the ^{12}CO $J = 2 \rightarrow 1$ line (*e*) (*thin line*). Vertical dashed lines indicate the extreme velocities of the molecular envelope. All the SiO spectra were taken with the high spectral resolution autocorrelators. The broad feature in the $v = 1$ $J = 2$–1 line of panels (*a*) and (*b*) was also observed in the 1 MHz and 100 kHz filters. The CO data correspond to the 1 MHz filters.

extreme velocities arises from a region spatially larger than that producing the bulk of the SiO maser emission (see Fig. 3). The observed size of the blue and red emission is 130 mas or 2.4×10^{14} cm, i.e., $\simeq 8$ stellar radii. If the velocity structure shown by the emission at extreme velocities corresponds to a bipolar outflow we could expect to observe weak emission extending in the blue and red wings of the SiO $v = 1$ $J = 2 \rightarrow 1$ line. This emission is well below our detection limit during the lunar occultations. In order to check this point, we did sensitive single-dish observations with the IRAM 30 m radio telescope in 1992 June and November. The data are shown in Figure 4. Broad wings were detected in the $J = 2 \rightarrow 1$ $v = 1$ SiO line in both observing periods. It is interesting to note that in both sessions we used different backends (1 MHz filters, 100 kHz filters, and two autocorrelators) and two receivers (a Schottky and a SIS) with different local oscillator and phase-lock chains. We are confident that the observed wings shown in Figure 4*a* and 4*b* are real and not arising from some instrumental effect. We also observed other maser lines of SiO (see Figs. 4*c* and 4*d*), and they also showed features at velocities larger than the expanding velocity of the external envelope as indicated by the CO $J = 2$–1 and SiO $J = 3$–2 $v = 0$ data of Figure 4*e*. The exact position from which this high-velocity emission arises is unknown. Nevertheless, our lunar occultation data in Figure 3 suggest that extreme and high-velocity emission are located further away from the star than those corresponding to the strong masers at intermediate velocities. The velocity depicted in Figure 3 indicates a non-spherical spatial distribution for the high velocities. Unfortunately it is not obvious to derive the mass-loss rate from the SiO maser emission in this bipolar mass-loss process.

Our lunar occultation observations show that high angular resolution can be achieved with a single telescope at millimeter wavelengths. The information we get from these data is complementary to that provided by VLBI experiments. In particular the total extent of the SiO masing regions at all velocities and the velocity field around the central star can be derived. Lunar occultations when combined with the size of the maser spots derived from VLBI can provide an unique tool for the study of the pumping mechanisms of the SiO masers and of the kinematics of the gas in the region of 2–10 stellar radii around the central star. A more detailed study including the analysis of the $J = 3 \rightarrow 2$ $v = 1$ SiO line is in progress and will be presented elsewhere.

J. Cernicharo thanks DGCICYT for partial support under project PB090-408. We thank the IRAM Granada staff for help during the observations. This paper was finished while J. C. was visiting astronomer at the MPIfR. He thanks the MPG and DGCICYT for financial support. We thank J. Alcolea, T. Krichbaum, P. Cox, A. Baudry, and C. Henkel for a critical reading of the manuscript.

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