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DETECTION OF $J = 5$–4 SiO MASERS IN LATE-TYPE STARS

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ABSTRACT

We have detected $v = 1, J = 5$–4 SiO maser emission from R Leo, χ Cyg, and VX Sgr and $v = 2$, $J = 5$–4 maser emission from VX Sgr. Upper limits are reported for maser emission in the $J = 6$–5, $v = 1$ and $v = 2$, and $J = 2$–1, $v = 3$ transitions toward several late-type stars. Maser photon emission rates for the high-J transitions which have been detected are roughly comparable to emission rates for the lower J transitions. Various maser pump mechanisms and emission regions are discussed, and published numerical models are compared with the observations. No single model emerges as the best explanation of SiO maser phenomena.

Subject headings: masers — stars: circumstellar shells — stars: long-period variables

I. INTRODUCTION

Vibrationally excited silicon monoxide masers may be the best probes of the physical conditions near the surfaces of late-type giant and supergiant stars. The range of temperature, density, and IR flux over which SiO maser action can occur is very restricted and constrains these masers to locations within 5–10 stellar radii of the star's surface. The information contained in the phenomenon of SiO maser emission can be exploited even further when all of the masering transitions are analyzed simultaneously. Unlike OH and H_2O, SiO has been shown to be masing in almost all (13 of 16) of its observed millimeter wavelength transitions, even though these lines are expected to originate in regions with quite different excitation conditions.

To date, time monitoring studies of the $J = 1$–0 and 2–1 lines (Hjalmarson and Olofsson 1979; Lane 1982) have attempted to search for correlations between maser and stellar properties that might help locate the masering regions, and VLBI studies (Moran *et al.* 1979; Lane *et al.* 1980; Lane 1982) have determined maser spot sizes and the spatial distribution of masers in different vibrational states. Both approaches will aid in determining the probable maser region locations, but only simultaneous observations of many maser lines can uncover the exact excitation conditions. The full utility of using SiO masers as tracers of late-type star environments can only be realized when both the SiO maser locations and the local conditions that lead to maser emission are known.

Unfortunately, the question of how SiO masers are excited has not been adequately answered. Several pumping mechanisms have been proposed which successfully explain the strong, low-J masers in the first and possibly second vibrational states. A crucial test for these models lies in their ability to predict correctly the existence and intensities of high-J masers and high vibrational state ($v = 3$) masers. The first observations of high-J masers in late-type stars were recently reported by Schwartz, Zuckerman, and Bologna (1982, hereafter SZB) as part of a multitransitional study. They found moderately strong $J = 3$–2 and 4–3 masers in five of the six sources searched, indicating that high-J masers are present in the atmospheres of late-type stars.

Observations of the SiO $J = 5$–4 and 6–5 transitions were recently made possible by the installation of the FCRAO[1] cooled Schottky 200–350 GHz receiver (Erickson 1981) on the 5 m antenna of the MWO[2] at Ft. Davis, Texas. This *Letter* presents the first detection of $v = 1$ and $v = 2$, $J = 5$–4 masers in late-type stars. We demonstrate that SiO maser emission is not dominated by the strong, low-J masers, as previously thought, but rather is characterized by a roughly constant maser photon luminosity in each of the rotational transitions observed to date. In addition, we have used the FCRAO 14 m antenna and cooled 70–120 GHz receiver to set improved upper limits on emission from the $v = 3$, $J = 2$–1 transition.

II. OBSERVATIONS

The MWO observations were performed during the period 1982 March 1–15, during which the low band,

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200–250 GHz, cooled receiver gave total single-sideband (SSB) system temperatures in the range 2000–3000 K for the $v = 1$ and $v = 2$, $J = 5$–4 transitions at 215.596037 and 214.088594 GHz, and 3000–4000 K for the $v = 1$ and $v = 2$, $J = 6$–5 transitions at 258.707489 and 256.898557 GHz (frequencies from Manson *et al.* 1977). The 128 channel, 250 KHz per channel, filter bank, with velocity resolutions of 0.35 and 0.29 km s^{-1} ($J = 5$–4, 6–5), was used for spectral analysis. Each 5–10 minute, position-switched scan was chopper vane calibrated. Atmospheric opacity was determined every 3–5 hours by antenna tipping. The antenna pointing, beam shape, and aperture efficiency were found from continuum scans across Jupiter, Venus, and Mars. The resultant sensitivities were 520 Jy ($J = 5$–4) and 770 Jy ($J = 6$–5) per degree of uncorrected antenna temperature. Errors in the sensitivities are about 10% and are primarily due to uncertainties in the brightness temperatures of the planets at these wavelengths (Lang 1978). The scatter in the measured beam sizes and planet antenna temperatures was quite small.

The continuum scans on the planets gave pointing corrections which were accurate to within $0'.1$ and reproducible to $0'.3$ on different days. We adopt a maximum pointing error of $0'.5$ on the maser sources which, when combined with the deconvolved beam sizes, leads to a maximum flux uncertainty of 30%. The polar telescope mount enabled tracking with constant polarization position angle; hence our reported fluxes represent twice the flux in the north-south linearly polarized mode. The calibration and pointing errors lead to a 35% uncertainty in the final flux values and limits reported for each source.

The FCRAO observations were performed on 1982 May 25 and 26. At 85.037959 GHz, the cooled receiver gave total SSB system temperatures between 400 and 700 K. Scans across Jupiter established pointing, beam size, and sensitivity (50 Jy/K). Both 100 kHz and 250 kHz per channel filter banks were used. Table 1 reports the 100 kHz upper limits since the velocity resolution for this spectrometer is similar to the resolution of the MWO observations; however, no low level emission was present in the 250 kHz filters either.

Our results are summarized in Table 1, which lists the flux and velocity of peak emission and the integrated flux for the detected lines. Nondetections are indicated by their 3 σ flux limit. Figure 1 shows spectra of the $v = 2$ and $v = 1$, $J = 5$–4 transitions of VX Sgr and the $v = 1$, $J = 5$–4 transitions of χ Cyg and R Leo. Stellar velocities of 6.0 km s^{-1} for VX Sgr (Moran *et al.* 1983), 9.5 km s^{-1} for χ Cyg (Lo and Bechis 1977), and -1.0 km s^{-1} for R Leo (Knapp *et al.* 1982) are indicated on Figure 1 by upward arrows. We were unable to detect $v = 3$, $J = 2$–1 emission in any of the five sources searched, and no strong $J = 6$–5 emission was found toward VY CMa ($v = 1$), R Leo ($v = 1$, $v = 2$), or χ Cyg ($v = 1$).

III. DISCUSSION

a) *Line Properties*

The spectra shown in Figure 1 have several attributes worth noting. First, the detected lines are simple in appearance. There is one strong, narrow feature near the stellar velocity for all three sources, with a suggestion of

TABLE 1

SUMMARY OF SiO MASER OBSERVATIONS

Source	Transition	Peak Flux (Jy)	Velocity of Peak (km s^{-1})	Integrated Flux (Jy × km s^{-1})
VY CMa ...	$J = 6$–5, $v = 1$	< 480	...	...
R Leo	$J = 2$–1, $v = 3$	< 9	...	...
	$J = 5$–4, $v = 1$	160 ± 42	−0.2	300
	$J = 5$–4, $v = 2$	< 150	...	...
	$J = 6$–5, $v = 1$	< 111	...	...
	$J = 6$–5, $v = 2$	< 540	...	...
W Hya......	$J = 2$–1, $v = 3$	< 12	...	...
	$J = 5$–4, $v = 1$	< 125	...	...
	$J = 5$–4, $v = 2$	< 200	...	...
VX Sgr......	$J = 2$–1, $v = 3$	< 6	...	...
	$J = 5$–4, $v = 1$	150 ± 26	4.4	720
	$J = 5$–4, $v = 2$	110 ± 32	4.0	200
χ Cyg.......	$J = 2$–1, $v = 3$	< 4	...	...
	$J = 5$–4, $v = 1$	235 ± 33	9.3	380
	$J = 5$–4, $v = 2$	< 150	...	...
	$J = 6$–5, $v = 1$	< 300	...	...
R Cas.......	$J = 2$–1, $v = 3$	< 4	...	...

NOTE.—Errors are 1 σ; upper limits are 3 σ.

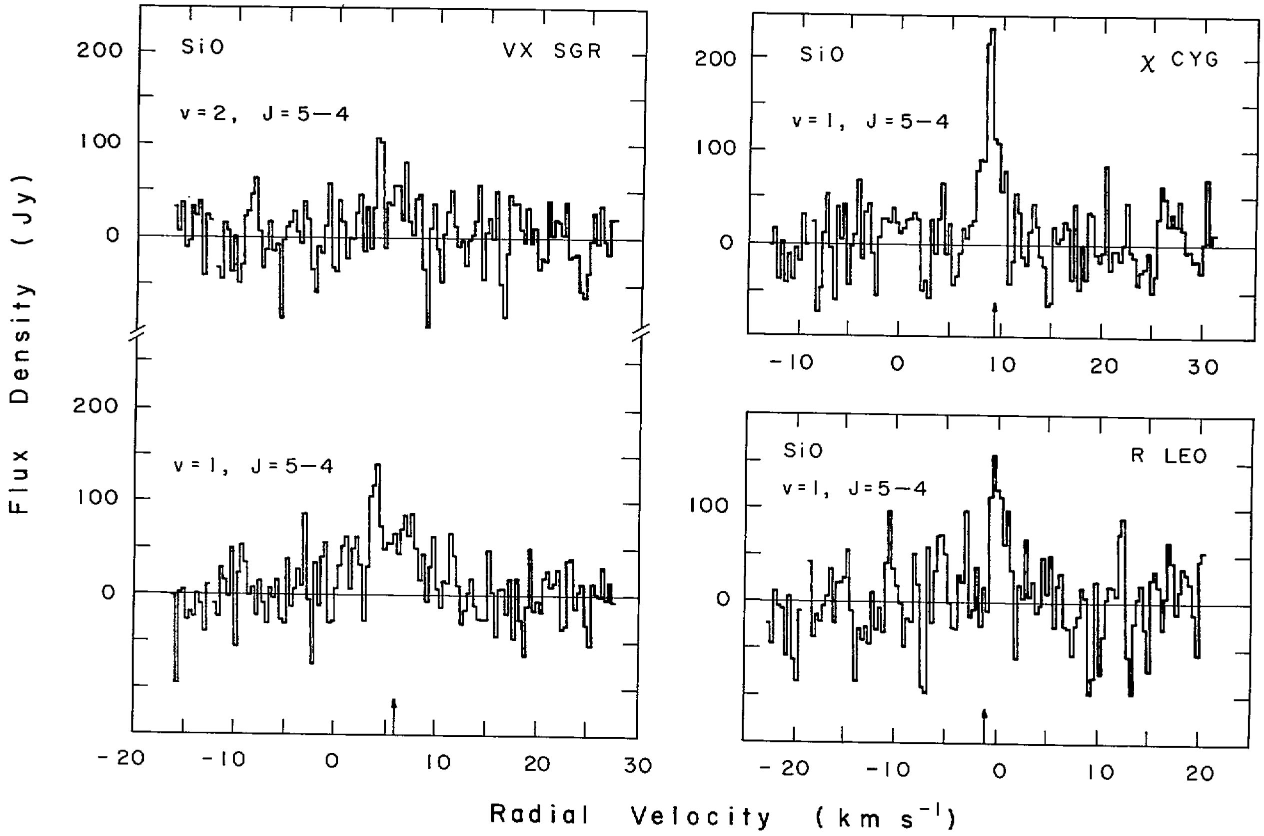

FIG. 1.—Spectra of SiO maser emission from VX Sgr, χ Cyg, and R Leo. Vertical arrows denote the stellar velocity.

weaker, broad emission in the VX Sgr $v = 1$ spectrum. Second, the lines are narrow, showing base widths of less than 5 km s^{-1} for the giant stars R Leo and χ Cyg and 10 km s^{-1} for the supergiant VX Sgr. Such differentiation between stellar types has been noted for the lower J masers, although the values of the widths are larger at lower J (Lane 1982).

The ratio of integrated fluxes for the $v = 1$ and $v = 2$ lines of a given J–J' transition is a useful discriminant of possible theoretical models of SiO maser emission. The ratios ($v = 1/v = 2$) for the lower J transitions are near 1–2 for J = 1–0 (Spencer *et al.* 1981; Lane 1982) and J = 3–2 (SZB), less than unity for J = 4–3 (SZB), and equal to or greater than 20 for J = 2–1 (Clark *et al.* 1981; Olofsson *et al.* 1981). For the J = 5–4 transition, the ratio is greater than 2.5 for R Leo and χ Cyg and equal to 3.3 for VX Sgr.

The most interesting property of the J = 5–4 lines is their strength. Although the peak antenna temperatures are very small (< 0.5 K), the photon emission rates are comparable to those seen in the low-J maser lines. The strength of the J = 5–4 lines is demonstrated in Figure 2, wherein the data from this work are combined with the time monitoring data of Lane (1982) and the single epoch data of SZB. In this figure, photon luminosity is plotted versus rotational transition number (for $v = 1, 2, 3$); vertical lines connecting symbols represent the range in luminosity due to time variability. It is evident from Figure 2 that *the number of maser photons leaving high-J transitions is similar to the number leaving low-J transitions*! Inspection of the data for χ Cyg reveals that, even if the large time variability seen in J = 1–0 occurs in every J–J' transition, maser photon luminosity is independent of rotational transition number. R Leo and VX Sgr show luminosity decreases near J = 3–2 and 4–3, but both sources have J = 5–4 luminosities comparable to the lowest J transitions. Figure 2 also shows that, while the $v = 3$ series is very weak compared with $v = 1$, the $v = 2$ rotational lines are relatively strong (except for the odd $v = 2, J$ = 2–1 transition).

b) *Comparison with Theory*

What effects do the J = 5–4 maser properties and the trends seen in Figure 2 have on the viability of current SiO maser theories? The two new facts, the strength of the J = 5–4 maser photon luminosity and the large $v = 2/v = 1$ ratio for J = 3–2, 4–3, and 5–4, are at

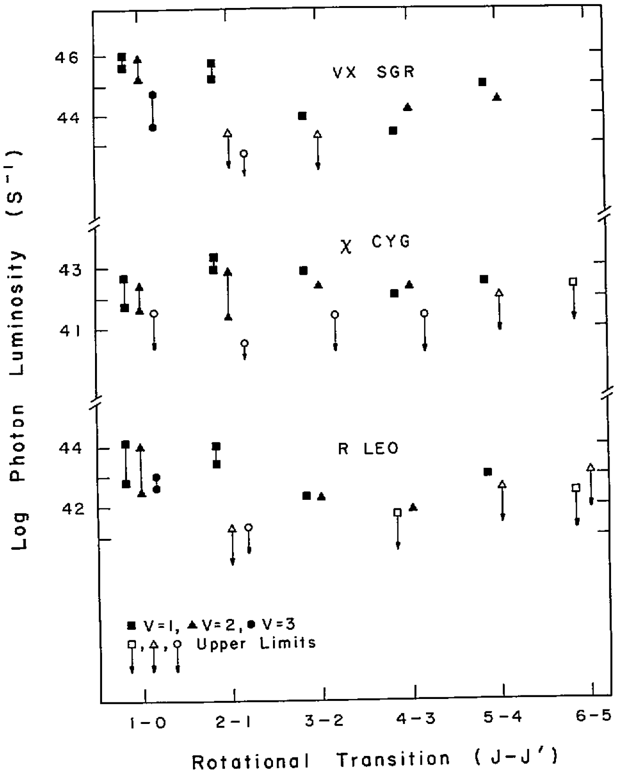

FIG. 2.—SiO maser photon luminosities from various rotational transitions for VX Sgr, χ Cyg, and R Leo. Symbols joined with a straight line show range of variability observed over a 2.5 yr period (Lane 1982). The data are from the following sources: $J = 1$–0 ($v = 1, 2, 3$), Lane (1982); $J = 2$–1 ($v = 1$), Lane (1982); $J = 2$–1 ($v = 2$), Olofsson *et al.* (1981) and Lane (1982); $J = 2$–1 ($v = 3$), this paper; $J = 3$–2 ($v = 1, 2, 3$), Schwartz, Zuckerman, and Bologna (1982); $J = 4$–3 ($v = 1, 2, 3$), Schwartz, Zuckerman, and Bologna (1982); $J = 5$–4 ($v = 1, 2$), this paper; $J = 6$–5 ($v = 1, 2$), this paper. For the $J = 3$–2 and 4–3 transitions of R Leo and VX Sgr, a line width of 1.5 km s^{-1} was assumed for each velocity feature tabulated by SZB. Distances adopted are 238 pc for R Leo (Lepine and Paes de Barros 1977), 132 pc for χ Cyg (Hinkle, Hall, and Ridgeway 1982), and 1500 pc for VX Sgr (Lockwood and Wing 1982).

odds with almost all current theories. (It should be noted in passing that *no* calculations predicting $J = 5$–4 masers have been performed because most simulations follow J levels to only 5 or 6.)

The radiatively pumped models of Kwan and Scoville (1974) are unable to invert levels above $J = 3$, although if the lower J levels are strongly saturated, the 3–2 maser luminosity can approach the 1–0 and 2–1 values. The collisionally pumped models of Watson, Elitzur, and Bieniek (1980) and Elitzur (1980) predict maser output dropping with increasing J *and* v. Our detection of $v = 2$, $J = 5$–4 and SZB's detections of $v = 2$, $J = 4$–3 are both at odds with the collisional models. The anisotropic escape models of Deguchi and Iguchi (1976) and Bujarrabal and Nguyen-Q-Rieu (1981) are able to produce both high-J masers (at least through $J = 4$–3 for the former reference) and the $v = 2$ series of rotational transitions in regions near the star ($\sim 1.5\ R_\star$). Unfortunately, the anisotropic escape models fail to explain the large separations (5–10 $R_\star$) of the $J = 1$–0 maser spots measured in VLBI experiments (Moran *et al.* 1979; Lane 1982) and the large observed total widths of the maser profiles (often greater than twice the expansion velocity). However, the possibility of having several regions of maser action cannot be easily dismissed (see Lane 1982 for discussion of $J = 1$–0 and 2–1 line formation), and placement of the masers around the star may be J dependent.

IV. SUMMARY

We have detected $v = 1$ and $v = 2$ maser emission from the $J = 5$–4 transition of SiO toward several late-type stars. The $v = 1$, $J = 5$–4 emission is strong and exhibits photon luminosities comparable to those in the $J = 1$–0, 2–1, 3–2, and 4–3 transitions. The $v = 2$, $J = 5$–4 line appears to be somewhat weaker than the $v = 1$ line. The velocity extent of emission in $J = 5$–4 shows the narrow (< 5 km s^{-1}) and wide (> 10 km s^{-1} at base) differentiation which separates giant from supergiant stars for the lower J maser lines. Detailed models of pump mechanisms predicting strong masers in high rotational transitions have not yet been developed, and maser models presented to date are at odds with recent observations.

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