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SiO MASERS IN VARIABLE STARS

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ABSTRACT

Eight new long-period variable stars were found with maser emission from the first excited vibrational state of silicon monoxide. One of these, W Andromedae, is a spectral type S star, the second S star known to show SiO emission. A second, T Cephei, is a borderline case between M and S. Although H_2O and OH maser emission is commonly found in the SiO stars, a search of 26 S-type stars for water has been negative, suggesting that the effect is real and arises from a chemical difference between the S stars and those of spectral type M. This may be a result of the high C/O ratio in spectral type S.

A new source of ground-state SiO emission was found in NGC 2264. This is the first thermal SiO emission observed in a molecular cloud outside of Sgr B2 and Orion A.

Subject headings: masers — radio sources: lines — stars: long-period variables — stars: S-type

I. INTRODUCTION

Maser emission from vibrationally excited SiO was first observed by Snyder and Buhl (1974) in Orion A; subsequently, 20 SiO maser stars were found by Kaifu, Buhl, and Snyder (1975), and Snyder and Buhl (1975). These stars are Mira-type and semiregular long-period variables, and all but three have water-vapor maser emission at 22 GHz. One of these three, χ Cyg, is a spectral type S star; such stars are thought to have a smaller free-oxygen supply than spectral type M stars and they show ZrO lines preferentially over the less stable TiO lines seen in M stars. (Snyder and Buhl 1975 originally reported R Hya as an S star SiO source, but the Kukarkin "S" designation is erroneous [P. Keenan, private communication].)

Because no S star has ever shown water emission, it seemed possible that the χ Cyg SiO maser reflected a basic difference in the chemistry of S and M stars. One purpose of this experiment was to look at a substantial number of bright S stars in both SiO and H_2O to see whether SiO masers are found in such stars and whether H_2O is ever present. We selected stars which possessed the characteristics shared by other H_2O–SiO stars: redness as indicated by their $I - K$ color index and, in the case of Mira variables, an optical variability of at least 5 mag. An attempt was also made to choose nearby stars, based on their visual or K-magnitude or a kinematic distance estimate.

II. OBSERVATIONS

The SiO observations were made with the 36 foot (11 m) telescope of the National Radio Astronomy Observatory,[1] Kitt Peak, Arizona. The $v = 1$, $J = 1 \rightarrow 0$ transition at 43,122.0 MHz was observed with a mixer-diode receiver whose single sideband temperature was ~1400 K. The $v = 1$, $J = 2 \rightarrow 1$ line (86,243.3 MHz) was observed with the cooled mixer receiver whose single sideband system temperature was ~600 K. Spectral information was provided by two filter banks of 256 channels each; the individual filters were 100 kHz in one case, and 250 kHz in the other. Total-power position switching was employed as the observing mode.

Observations of the $J = 6_{16} \rightarrow 5_{23}$ rotational line of water vapor (22,235.08 MHz) were made on the 120 foot (37 m) paraboloid of the Haystack Observatory,[2] Westford, Massachusetts. The system has a maser front end with a 100 channel autocorrelator providing spectral information. System temperature lay between 100 K and 200 K, depending on the weather. Total-power position switching was used here, too, with the exception that off-source runs were made to track the same sky path as the on-source runs to prevent adverse effects on the maser gain due to changes in the Earth's magnetic field.

The primary search was conducted at 43 GHz with some search work being done at 86 GHz. A total of 83 sources was examined. Near-coincidence with solar right ascension made it necessary to observe some sources with the dome closed to prevent thermal deformation of the antenna. Stars detected in this manner have been so noted.

III. RESULTS

Eight new stars have been detected with vibrationally excited SiO emission, bringing the total of such stars

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

[2] The Haystack Observatory is operated by the Northeast Radio Observatory Corporation with support from the National Science Foundation.

TABLE 1

NEW DETECTIONS

Name	IRC	Frequency (GHz)	T_{ant}* (K)	ΔV (km s^{-1})	Velocity (km s^{-1})
CIT 3..........	+10011	86	1.1	~3	+8
W And........	+40037	43	0.6	2.1	−34
		86	0.7	3.8	−33
R Cnc.........	+10185	43	2.2	3.5	+19
		86	2.1, 2.0	~2, ~3	+19, 13.8
RU Her........	+30282	43	0.9	1.8	−11.5
		86	1.3	2.7	−11.5
AH Sco........	−30282	43	1.0	4.9	+0.7
		86	~1	~4	~ −2
	−20424	43	0.5	3.8	+15.0
	−10529	43	2.0	~1	−17.0
			2.5	~1.5	−19.0
T Cep.........	+70168	43	1.0	2.4	−1.4
		86	1.4	~3.5	−1.7

to 31. Three are S-type, 15 are oxygen-rich Mira variables, six are semiregular variables, and one is an irregular variable. The remainder are not optically identified. Table 1 gives identification, antenna temperature (corrected to outside the Earth's atmosphere for a lossless antenna), line width, and velocity (LSR) for both frequencies (where appropriate). The lines are, in general, weak, and the error in velocity and line width is, conservatively, ± 0.8 km s^{-1}. We comment briefly on individual sources.

The infrared source IRC +10011 (Fig. 1) has no counterpart in the *General Catalogue of Variable Stars* (Kukarkin *et al.* 1969). It is a highly reddened object with a visual magnitude greater than 20. Zappala *et al.* (1974) identify it as an oxygen-rich Mira variable on the basis of its 650-day period, *K*-magnitude (1.63), and infrared spectrophotometry. Its $I - K$ index is 7.60 in the *Two-Micron Sky Survey* (Neugebauer and Leighton 1969). It has OH emission at 27 km s^{-1} and

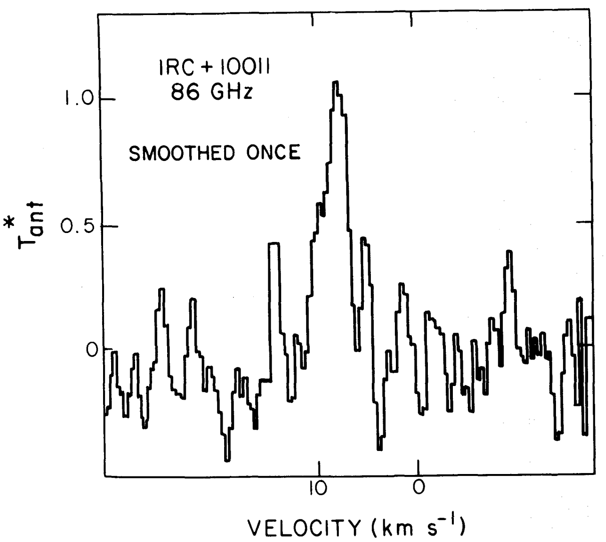

FIG. 1.—The 86 GHz SiO ($J = 2 \rightarrow 1, v = 1$) spectrum of IRC +10011 (CIT 3).

−9 km s^{-1} and an H_2O line at 22 km s^{-1} (Wilson and Barrett 1972; Dickinson 1976). IRC +10011 was searched in SiO only at 86 GHz.

W And (Fig. 2) is a Mira-type star classed as S6.1e by Kukarkin. W And is the second S star to show emission from vibrationally excited SiO. W And has been twice examined for H_2O and has been negative to less than 3 Jy despite the fact that its visual magnitude changes from 6.7 to 14.5 mag, its *K*-magnitude is 0.88, and its $I - K$ index is 5.60—all three quantities being good indications of possible water emission in oxygen-rich Mira variables. It is also negative in OH (Wilson and Barrett 1972). We have searched 26 S stars for H_2O to a level of, typically, 5 Jy. They include: R And, RR And, W And, W Aql, R Cam, T Cam, V Cnc, RS Cnc, S Cas, U Cas, WY Cas, T CMi, T Cep, W Cet, AA Cyg, R Cyg, S Cyg, χ Cyg, R Gem, T Gem, ST Her, R Lyn, SX Peg, T Sgr, ST Sgr, and S UMa. All are negative.

The star R Cnc (Fig. 3) has two strong features at 86 GHz at 19 km s^{-1} and 13.8 km s^{-1}. By contrast, the 43 GHz emission shows only the 19 km s^{-1} clearly; a weak noiselike spike is the only suggestion of the lower velocity feature. R Cnc is a Mira variable which is quite bright both visually (6.2 mag) and at 2.2 μm (−0.74 mag). It is spectral type M6–M8. It is negative in H_2O. Its visual magnitude differential (6.2–11.8) is low; all Miras with water emission show a change of more than 6 mag (Dickinson 1976). It is also negative in OH at 1612, 1665, and 1667 MHz to about 1 Jy (Wilson and Barrett 1972). This SiO maser was discovered independently by Spencer *et al.* (1976).

In RU Her (Fig. 4), the sharp, narrow feature at 43 GHz suggests that the wider 86 GHz feature is actually a blend of two features at −11.5 km s^{-1} and −10 km s^{-1}. A relatively long-period Mira variable (485 days), RU Her is spectral type M6–M7. It has been searched on three different occasions for OH and H_2O without success—despite the fact that its infrared and optical properties are typical of such stars.

AH Sco (Fig. 5) is a semiregular variable, M3, recently detected in the water line by Lepine, Paes de Barros, and Gammon (1976). It has an unusually long

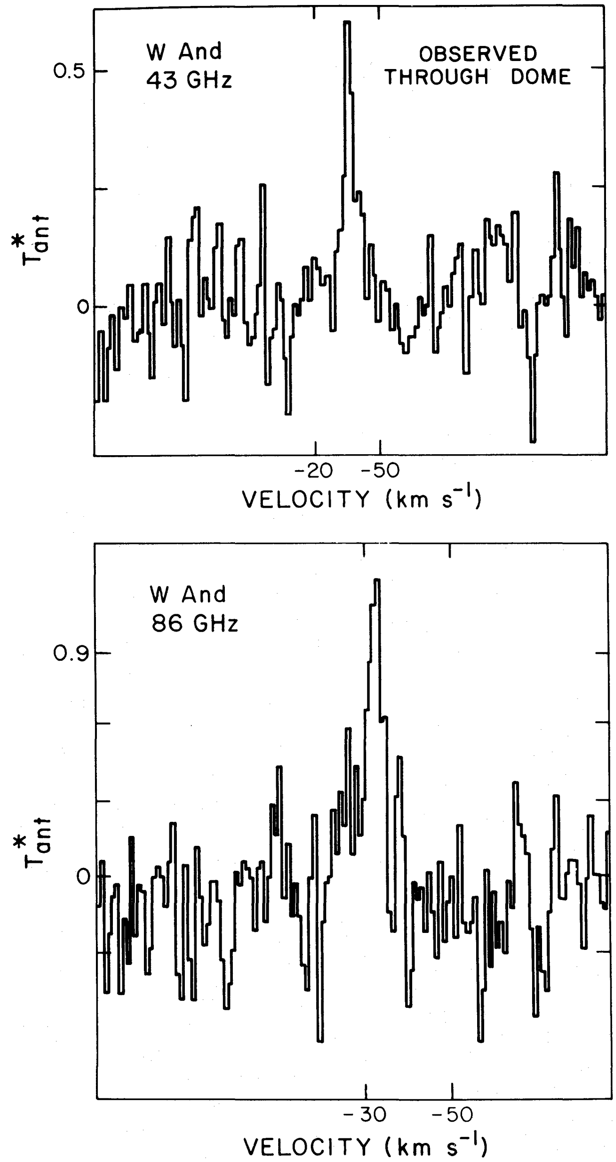

FIG. 2.—The SiO (v = 1) rotational spectra of W And (IRC +40037) at 43 GHz ($J = 1 \rightarrow 0$) and 86 GHz ($J = 2 \rightarrow 1$). To convert to heliocentric velocity, add −0.2 km s^{-1}.

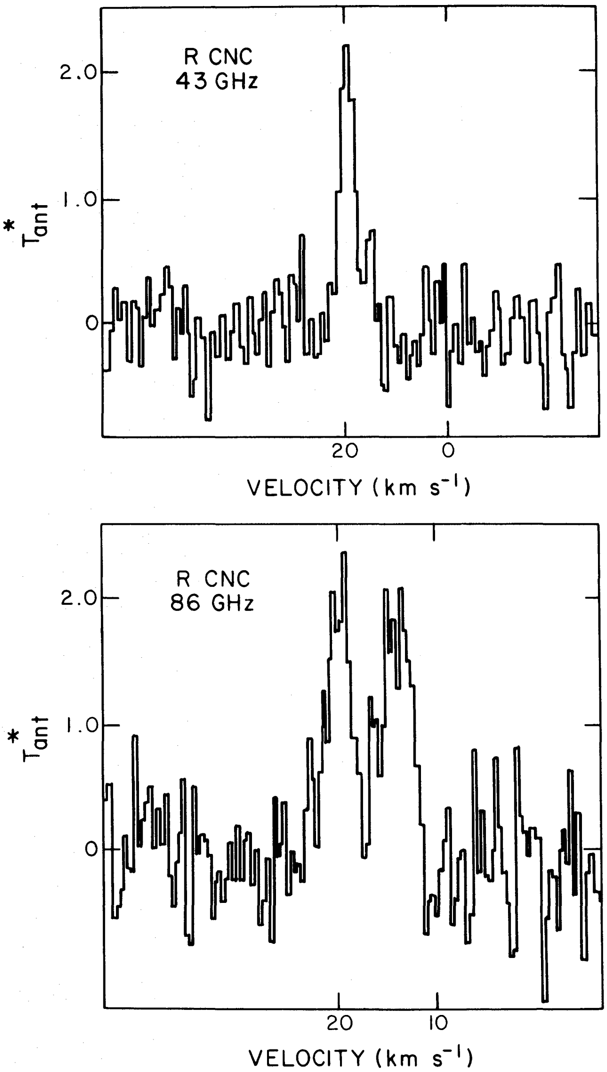

FIG. 3.—The SiO (v = 1) rotational spectra of R Cnc (IRC +10185) at 43 GHz ($J = 1 \rightarrow 0$) and 86 GHz ($J = 2 \rightarrow 1$). To convert to heliocentric velocity, add 12.2 km s^{-1}.

period, 714 days. The 43 GHz SiO line is apparently a single feature. It appears to be present also at 86 GHz, although time did not permit us to integrate down the noise. AH Sco has a K-magnitude of 0.32 and an $I - K$ color index of 3.99. A. Baudry (private communication) has recently detected a double-peaked OH spectrum from this star. The velocity separation is ~40 km s^{-1}, which confirms nicely the correlation between period and radial-velocity pattern (Dickinson, Kollberg, and Yngvesson 1975).

IRC −20424 (Fig. 6) has a substantial infrared excess from circumstellar dust which is probably also responsible for obscuring the optical object within. Its $I - K$ index is 6.31; its K-magnitude (0.90) makes it a relatively bright infrared source. Water emission is seen at 18.8 km s^{-1}, and the double group of OH emission features, characteristic of infrared stars, is also present (Dickinson, Bechis, and Barrett 1973; Wilson *et al.* 1972).

IRC −10529 is a type IIb OH source, negative in water emission (Wilson and Barrett 1972; Dickinson 1976). It exhibits the characteristic double-peaked OH spectrum but has, unexpectedly, an intermediate velocity component at 1665 MHz and 1667 MHz which is 80% left circularly polarized. The two SiO emission features in Figure 7 bracket this feature. Its K-magnitude is 2.65, and it is highly reddened with an $I - K$ of 6.77.

T Cep shows a single feature at 43 GHz (Fig. 8). The higher frequency spectrum suggests there may be more than one peak, but the signal-to-noise ratio is too poor

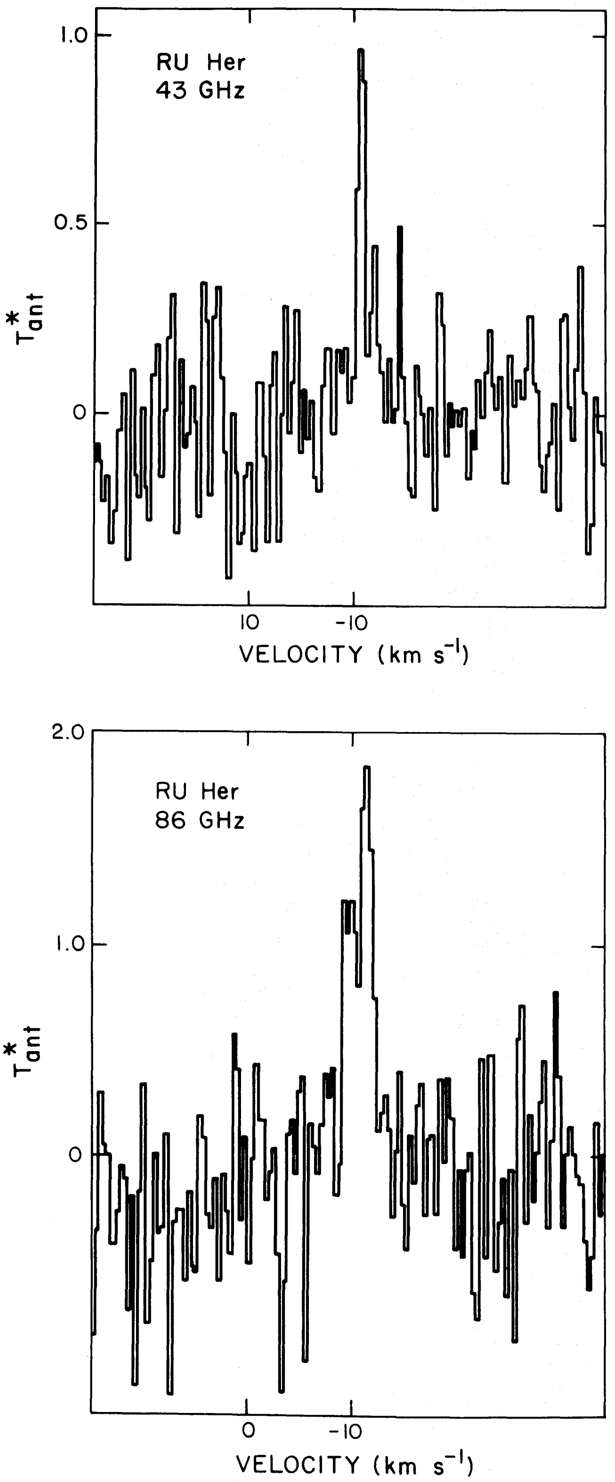

FIG. 4.—The SiO (v = 1) rotational spectra of RU Her (IRC +30282) at 43 GHz ($J = 1 \rightarrow 0$) and 86 GHz ($J = 2 \rightarrow 1$). To convert to heliocentric velocity, add −18.0 km s^{-1}.

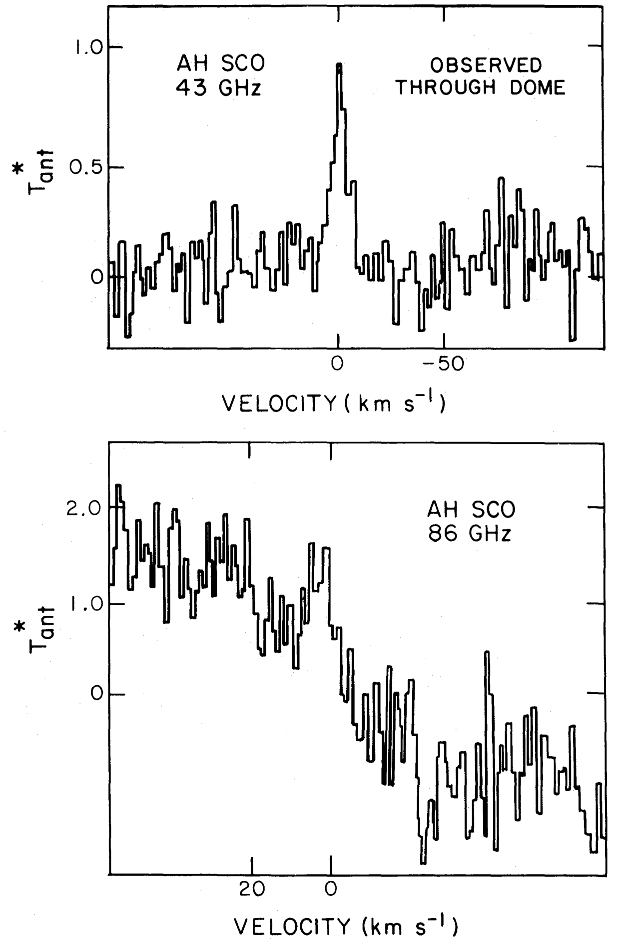

FIG. 5.—The SiO (v = 1) rotational spectra of AH Sco (IRC −30282) at 43 GHz ($J = 1 \rightarrow 0$) and 86 GHz ($J = 2 \rightarrow 1$). To convert to heliocentric velocity, add −7.5 km s^{-1}.

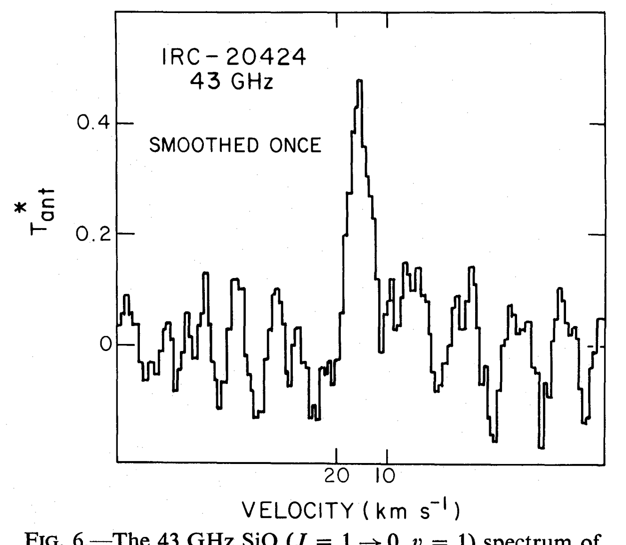

FIG. 6.—The 43 GHz SiO ($J = 1 \rightarrow 0$, v = 1) spectrum of IRC −20424.

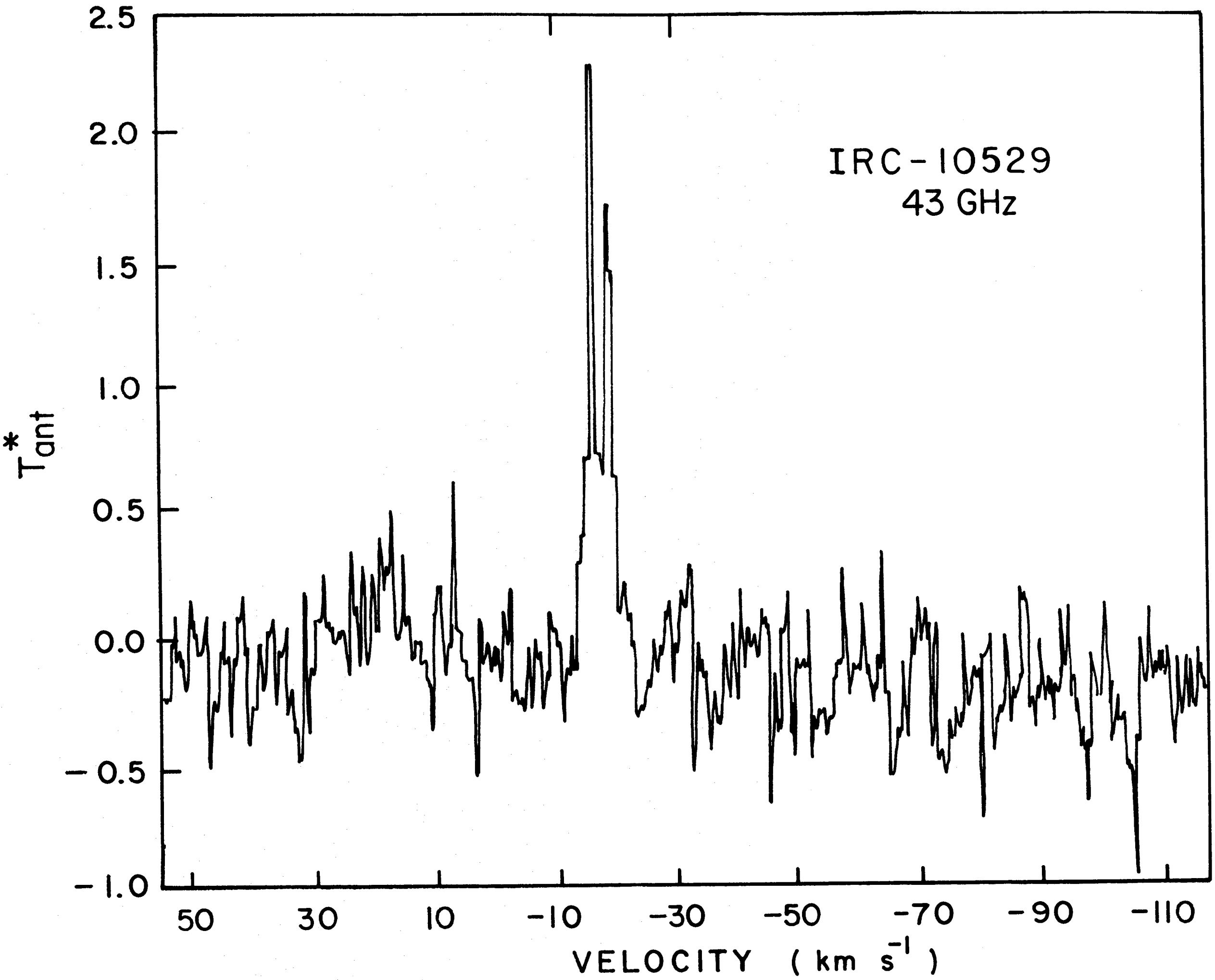

FIG. 7.—The 43 GHz SiO ($J = 1 \rightarrow 0$, $v = 1$) spectrum of IRC −10529

to tell with certainty. It has been searched for water on three different occasions without success. It is an extremely bright infrared object ($K = -1.56$), and its visual change goes from 5.4 to 11.0 mag. Listed as M5e–M9e by Kukarkin *et al.* (1969), it was classified as an S star by Spinrad and Newburn (1965), but it is really between M and S on the basis of subsequent spectra (Keenan, private communication). This source was found independently by Spencer *et al.* (1976).

Concerning NGC 2264 (Fig. 9), while completing some calibration work on the ground vibrational state, $J = 2 \rightarrow 1$ line of SiO (86,846.85 MHz), we observed a new emission line, the first ground-state SiO emission from a molecular cloud seen outside of Sgr B2 and Orion A. The telescope was pointed at $\alpha_{1950} = 6^h38^m28^s.4$, $\delta_{1950} = 9°32'12''$, 55″ from the position of Allen's near-infrared source (Allen 1972). The line is 2 km s^{-1} broad and has a peculiar velocity of about 7.5 km s^{-1}. This is one-half to one-third the line width of molecular emission lines in NGC 2264. NGC 2264 has not yet been searched for vibrationally excited SiO emission and clearly warrants additional work.

a) *Infrared* SiO *Study*

Since most theoretical models of maser emission invoke some form of infrared pumping (Mather and Litvak 1974; Kwan and Scoville 1974), we have investigated the relation of SiO $v = 1, J = 1 \rightarrow 0$ flux with 4.8 and 10 μm flux for all known SiO maser sources. Such pumping could occur in SiO via the lowest vibrational transition at ~ 8 μm or its first overtone at ~ 4 μm. We note that, subject to infrared and SiO variability, there is a rough correlation in the data plotted in Figure 10. The scatter in the infrared data in Figure 7 is on the order of the variability observed by Forrest, Gillett, and Stein (1975). We plot peak SiO flux (W m^{-2} Hz^{-1}) because the narrowness of the maser lines renders them unresolved by the 100 kHz filters in many cases. This causes the points in Figure 10 for sources with exceptionally narrow lines to appear to the left of their true position in the diagram. The equal photon of 100% efficiency line drawn in Figure 10 is calculated by assuming equal fractional line widths for the infrared pumping line

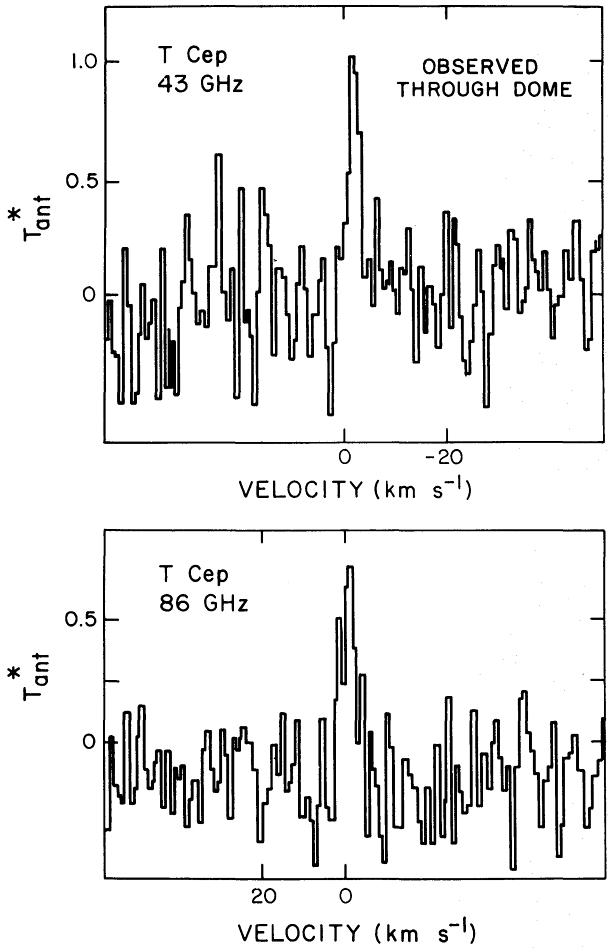

FIG. 8.—The SiO ($v = 1$) rotational spectra of T Cep (IRC +70168) at 43 GHz ($J = 1 \rightarrow 0$) and 86 GHz ($J = 2 \rightarrow 1$). To convert to heliocentric velocity, add -13.7 km s^{-1}.

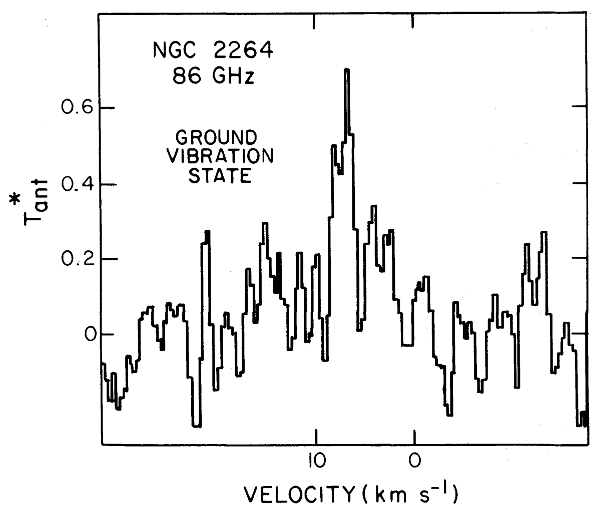

FIG. 9.—The ground-state ($v = 0$) SiO rotational spectrum of NGC 2264 at 86 GHz ($J = 2 \rightarrow 1$).

and the 43.1 GHz maser line. Because the maser lines may be narrower than the thermal Doppler width, the 100% efficiency line shown is the most stringent that can be chosen as a test of IR pumping. Even more striking than the rough correlation discussed above is the abrupt cutoff of sources just short of the 100% efficiency line. While this type of comparison does not prove the existence of infrared pumping, it provides a plausible consistency check. Finally, we note that Orion A is the only source which violates this check. The deep 10 μm silicate absorption in Orion suggests that there is much more dust present than exists in the shells about the SiO maser stars; thus the 4.8 μm flux could be heavily attenuated, causing Orion to fall to the right of the "100% efficiency" line. We call attention to the fact, however, that a number of Orion-like objects have been observed (i.e., Mon R2, S140 IR, etc.) and show no SiO maser emission. Orion appears to be a unique object, and infrared pumping, conceivably, does not apply.

IV. DISCUSSION

Traditionally, S stars are those long-period variables where ZrO lines become prominent at the expense of the TiO emission usually seen in spectral type M stars. S stars have a higher C/O ratio than the oxygen-rich M stars. Scalo (1974) has done detailed calculations on molecular abundances for varying C/O ratios: we reproduce, for convenience, the appropriate figure from his paper (Fig. 11). The abscissa can be thought of as grading from M stars on the left, to S stars near C/O = 0.9. Further increase in the C/O ratio leads one to the domain of carbon stars. (There may, in fact, be an evolutionary sequence in long-period variables from M through S to C in spectral type [Scalo 1974].) While the H_2O/SiO ratio remains roughly constant over a significant range of C/O values, the SiO eventually dominates, being an order of magnitude larger than H_2O for a short while near C/O = 0.95. This is consistent with our ability to detect a limited number of SiO masers in S stars but no H_2O masers.

Table 2 lists 76 sources searched at 43 GHz for excited vibrational state SiO emission. Upper limits varied somewhat, but were, typically, 0.5 K in the 250 kHz filters and 0.75 K in the 100 kHz filters. Distance was an important factor in detectability. At least five of the SiO stars, W And, R Cnc, RU Her, T Cep, and IRC +10011, are thought to be within 500 pc. For convenience, Table 3 lists all SiO maser stars known at this writing.

The three water-emission stars have properties as characterized by Snyder and Buhl (1975). IRC +10011 is a type IIb OH source, the SiO velocity falling near the high-velocity OH peak. IRC −20424 is a type I OH source with its SiO emission about 3 km s^{-1} less than the high-velocity OH. Of the five SiO stars which show neither OH nor H_2O, two are S stars, χ Cyg and W And, and may be expected to be negative for the reasons previously discussed. R Cnc, as noted, lacks the large differential magnitude change characteristic of OH/H_2O sources. The remaining star, RU Her, is

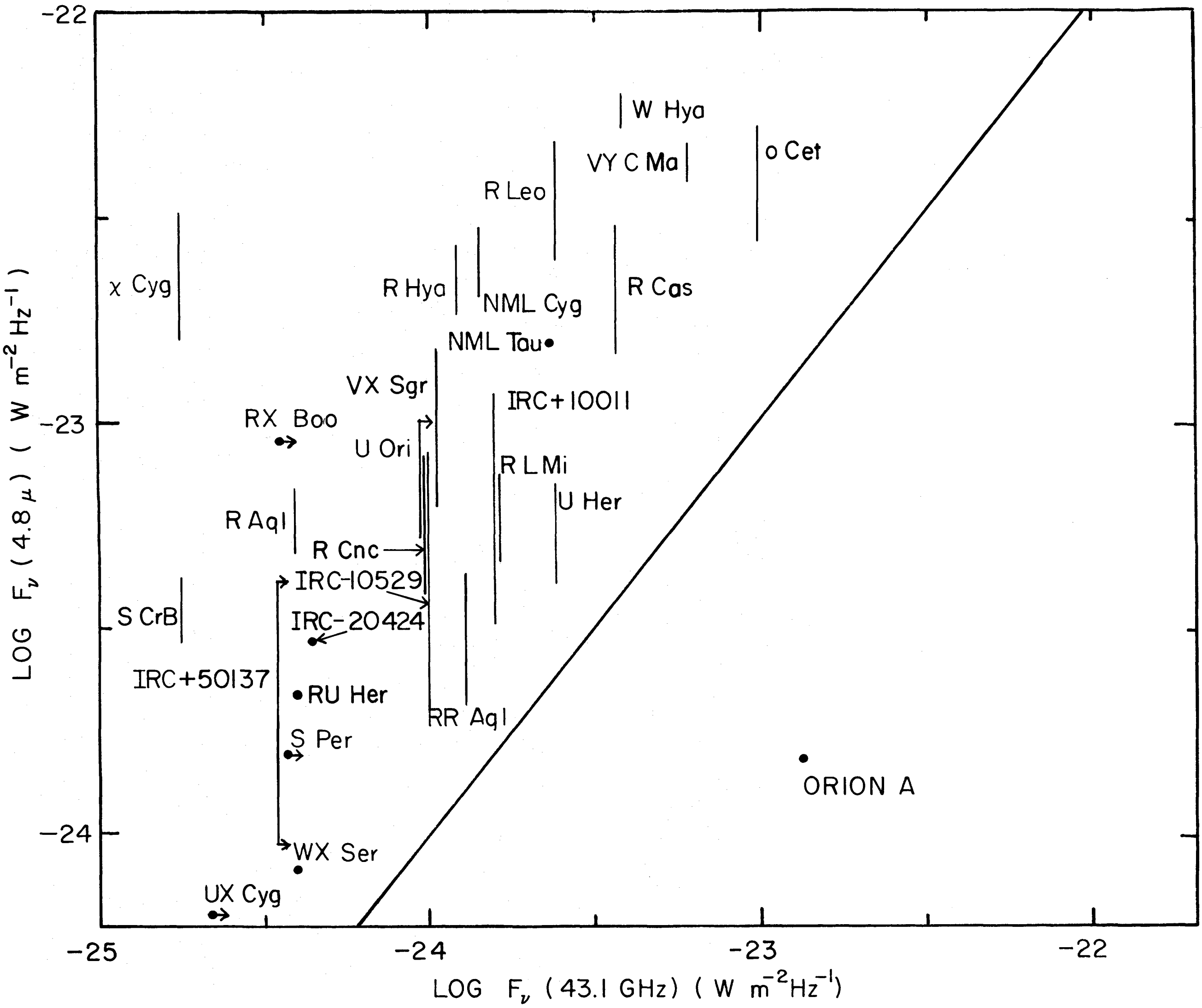

FIG. 10.—The peak flux density at 43.1 GHz is plotted versus the 4.8 μm flux density for all known SiO masers. The range of infrared variability is used where available. The 45° line corresponds to equal number of photons at 43.1 GHz and 4.8 μm. All 43.1 GHz data (except for sources reported herein) are from Snyder and Buhl 1975. The infrared data are from Becklin *et al.* 1973, Forrest *et al.* 1975, Gehrz and Woolf 1971, Hyland *et al.* 1972, and Wilson *et al.* 1972.

still a puzzle; it possesses all the indicators of OH and H_2O maser stars, but has, as yet, not rewarded us with a detection.

We note in closing that, since publication of Snyder and Buhl (1975) and Kaifu, Buhl, and Snyder (1975), WX Ser has shown 22 GHz water emission and S Per has been seen in both OH and H_2O (Dickinson, Kollberg, and Yngvesson 1975; Dickinson 1976). They join the 15 other SiO stars which also show OH and H_2O. RX Boo shows SiO and H_2O but not OH. IRC +50137 has SiO and OH but not H_2O; this may be only a sensitivity problem, as the SiO emission is marginal and the *K*-magnitude is 2.72—very dim.

We have also looked at a number of objects which resemble the Becklin-Neugebauer object in Orion: W33 A, W33 B, Onsala 1, NGC 7538, Mon R2, and S140 IR. All are strong near-infrared sources without radio continuum. All are negative in SiO excited state emission, suggesting that the BN object is unique and may not be properly classifiable with these other sources.

We wish to thank Drs. Pat Thaddeus and J. H. Davis for assistance with some of the observations and Dr. Tom Barnes for making available his compilation of radial velocities and kinematic distances of late-type stars. G. N. B. was supported in part by the National Science Foundation under grant MPS 05070-76.

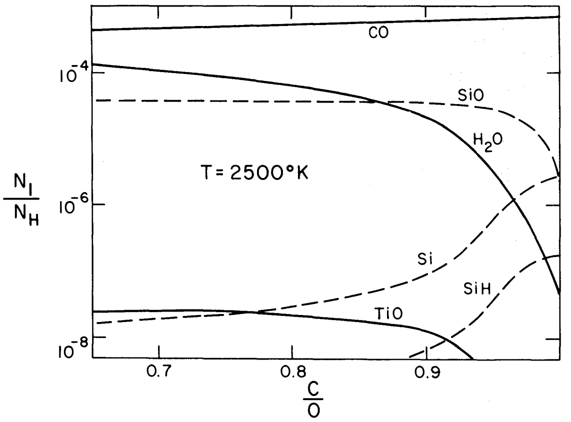

FIG. 11.—Variation with C/O of the concentration of observable molecules relative to hydrogen for a temperature of 2500 K. The oxygen abundance is 7×10^{-4} and the gas pressure is 10^3 dynes cm^{-2}.

TABLE 2

NEGATIVE RESULTS (43 GHz)

R And	χ CrB	S UMa
χ And	R Crt	T UMa
RR And	AA Cyg	U UMi
RW And	Z Del	R Vir
χ Aqr	R Gem	S Vir
W Aql	T Gem	U Vir
R Aur	S Her	RT Vir
U Aur	T Hya	AFCRL 618
TV Aur	χ Hya	AFCRL 19
R Boo	R Lyn	W 33 A (IR)
R Cam	V Mon	W 33 B
T Cam	BD Mon	HD 11979
V Cnc	FU Mon	Onsala 1
W Cnc	R Oph	NGC 7538
S CMi	χ Oph	IRC +30292
V CMi	RZ Per	Mon R2
R CVn	Z Pup	S140 IR
U CVn	T Sgr	OH 21.5+0.5
Y CVn	ST Sgr	OH 26.5+0.6
S Cas	V745 Sgr	OH 30.1−0.2
U Cas	RR Sco	OH 30.1−0.7
Y Cas	ST Sco	OH 32.8−0.3
MY Cep	V407 Sco	OH 45.5+0.1
R Com	R Ser	OH 231.4+4.2
T CrB	EI Tau	
W CrB	R UMa	

TABLE 3

A CATALOG OF SiO MASER STARS

Star	IRC	α_{1250}	δ_{1950}	References	Notes
CIT 3..................	+10011	01ʰ03ᵐ49ˢ	+12°18′42″	1	M, OH, H_2O
W And................	+40037	02 14 23	+44 04 28	1	S
o Cet..................	+00030	02 16 49	−03 12 12	2	M, OH, H_2O
S Per..................	+60088	02 19 16	+58 21 30	3	SR, OH, H_2O
NML Tau..............	+10050	03 50 46	+11 15 42	2	SR, OH, H_2O
TX Cam...............	+60150	04 56 44	+56 06 54	4	M
	+50137	05 07 20	+52 48 48	3	
Ori A..................	...	05 32 46.9	−05 24 18	2	OH, H_2O
U Ori..................	+20127	05 52 51	+20 10 06	3	M, OH, H_2O
	+60169	06 30 02	+60 58 54	4	
VY CMa...............	−30087	07 20 55	−25 40 11	2	Irr, OH, H_2O
R Cnc.................	+10185	08 13 49	+11 52 54	1, 4	M
R Leo.................	+10215	09 44 52	+11 39 42	2	M, OH, H_2O
R Hya.................	...	13 26 59	−23 01 30	2	M
W Hya.................	−30207	13 46 12.2	−28 07 03	2	SR, OH, H_2O
RX Boo...............	+30257	14 21 58	+25 55 53	3	SR, H_2O
S CrB..................	+30272	15 19 21.4	+31 32 45	2	M, OH, H_2O
WX Ser................	+20281	15 25 32	+19 44 24	2	M, OH, H_2O
RU Her................	+30283	16 08 07	+25 12 00	1	M
U Her..................	+20298	16 23 34.6	+19 00 18	2	M, OH, H_2O
AH Sco................	−30282	17 08 03	−32 16 00	1	SR, OH, H_2O
	−20424	18 00 58	−20 19 12	1	OH, H_2O
VX Sgr................	−20431	18 05 03.2	−22 14 06	2	SR, OH, H_2O
R Aql..................	+10406	19 03 57.7	+08 09 11	2	M, OH, H_2O
χ Cyg..................	+30395	18 48 38	+32 47 12	2	S
RR Aql................	+00458	19 55 01	−02 01 12	2	M, OH, H_2O
	+10529	20 07 46	−06 24 42	1	OH
NML Cyg..............	+40448	20 44 33.8	+39 55 56	2	OH, H_2O
T Cep..................	+70168	21 08 52	+68 17 24	1, 4	S
R Peg..................	+10527	23 04 07	+10 16 24	4	M, OH, H_2O
R Cas..................	+50484	23 55	+51 06 36	2	M, OH, H_2O

REFERENCES.—1, this paper and Dickinson and Blair 1976; 2, Snyder and Buhl 1975; 3, Kaifu, Buhl, and Snyder 1975; 4, Spencer *et al.* 1976.

NOTES.—M, oxygen-rich Mira variable; S, S-type Mira; SR, semiregular variable; H_2O, water emission; Irr, irregular variable.

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Note added in proof.—IRC +10011 has subsequently shown 43 GHz excited state SiO emission at ~ 28 km s^{-1}, in agreement with the high-velocity OH feature.

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