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A SEARCH FOR 183 GHz EMISSION FROM WATER IN LATE-TYPE STARS

T. B. H. KUIPER, P. N. SWANSON, D. F. DICKINSON,[1] E. N. RODRIGUEZ KUIPER,[2] AND P. ZIMMERMANN
Jet Propulsion Laboratory, California Institute of Technology
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ABSTRACT

A search was made for 183 GHz line emission from water vapor in the direction of 12 Mira and two semiregular variables. Upper limits to the emission are in the range of 2000 to 5000 Jy. It is estimated that thermal emission from the inner regions of late-type stellar envelopes will be on the order of 10 Jy. Maser emission, according to one model, would be an order of magnitude stronger. From the limited set sampled, the possibility of very strong maser emission at 183 GHz cannot yet be ruled out.

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

I. INTRODUCTION

Molecular line spectra at centimeter and millimeter wavelengths have proved useful in determining the conditions in the envelopes surrounding giant and supergiant stars of late spectral type. They have shed light on the gas-phase composition, isotopic abundances, radial structure of temperature and density, and mass loss rates (e.g., Zuckerman 1980*a*, *b*). While maser transitions are more difficult to interpret than transitions between thermally populated levels, their sensitivity to particular combinations of environmental parameters gives them the potential of being rather fine probes of specific regions around a star. Water vapor emission at 22 GHz arises in the acceleration region of the envelope within a few stellar radii of the star ($\sim 10^{14}$ cm), where the temperature is 1000–2000 K (Vardya 1970; Goldreich 1980). SiO masers also occur in the inner region of the envelope. 1612 MHz OH masers occur at >1000 stellar radii ($>10^{16}$ cm; e.g., Bowers, Johnston, and Spencer 1981), where the temperature is ~ 100 K (Elitzur, Goldreich, and Scoville 1976).

Another potential maser probe of stellar envelopes is the 183 GHz line of water. In modeling the excitation of water in circumstellar envelopes, Deguchi (1977) has predicted an inversion of the 183 GHz transition. That this transition does indeed invert under suitable conditions is demonstrated by the intensity of the wide wings of this line seen toward Orion KL (Kuiper, Zuckerman, and Rodriguez Kuiper 1981), and the variability of the emission from this source (Kuiper *et al.* 1984). However, the conditions in the region in Orion where this emission arises are believed to be quite different from the stellar conditions modeled by Deguchi. A credible *a priori* prediction of 183 GHz emission in any actual region is probably out of the question because the physical parameters of such regions are not sufficiently well known (Goldreich 1980). We were therefore motivated to make a search for possible 183 GHz maser emission in the envelopes of late-type giants and supergiants.

Because of the limited amount of observing time available at our observing altitude, we chose a strategy of surveying a large number of stars for strong emission, spending between 0.5 and 1 hour on each star. We selected the stars primarily on the basis of OH and 22 GHz H_2O maser emission. Eleven of the 14 stars we observed have such maser emission (Kleinmann, Dickinson, and Sargent 1978). This criterion selects late M stars with [O] > [C] (Vardya 1970; Wyckoff and Clegg 1978), and therefore those with generally lower mass-loss rates (Zuckerman 1980*a*, *b*; Knapp *et al.* 1982). A number of preferred candidates could not be observed because they were not visible above 35° elevation at night on our assigned flight dates, because they could not be included in an efficient flight plan, or because of equipment failure. The stars observed are listed in Table 1.

II. OBSERVATIONS

The observations were made in 1980 February and August with a cooled Schottky-diode receiver mounted on the 91 cm telescope of the G. P. Kuiper Airborne Observatory. The equipment used and the details of the calibration are extensively described in Kuiper *et al.* (1984). We present here only a summary and additional facts of particular relevance to the observations described in this paper.

The system temperature was ~ 900 K, double sideband. The aperture efficiency was 0.40, giving a sensitivity of 10^4 Jy K^{-1}. Typically, an rms noise level of 0.1 K was achieved in 0.5 hour. Pointing was done by tracking the star observed, or an adjacent star, in a co-aligned tracking telescope, and is estimated to be accurate to $\sim 10''$, which is a negligible fraction of the $8'$ beamwidth.

Two spectrometers were used. A 36 channel filter bank has 11 1 MHz channels covering the central 11 MHz, 12 3 MHz channels covering the ranges from 4.5 to 22.5 MHz above and below the receiver's center frequency, and 10 8 MHz filters covering the ranges from 12 to 52 MHz relative to the center. (In addition, there were three broad-band channels.) The other spectrometer was a digital FFT device, covering the central 10 MHz with 256 channels, for any narrow spectral features that might be detected.

The principal obstacle to achieving the theoretical sensitivity of the receiver for broad lines proved to be severe standing waves in the telescope. To minimize these as much as possible, we observed by chopping the subreflector in azimuth, symmetrically about the optical axis of the telescope. The total throw of the telescope beam was two beamwidths. The optical axis of the telescope was positioned one beamwidth either left or right of the star being observed. The signal received from the direction of the star and that from the blank sky on the

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[1] While an employee of Ball Aerospace Systems Division working at JPL.

[2] While an NAS-NRC Senior Resident Research Associate.

TABLE 1

RESULT OF SEARCH FOR 183 GHz LINE EMISSION

Star	Spectral Type	Var. Type	Receiver Central V_{lsr} ($km\ s^{-1}$)	Max S (Jy)	D (kpc)	dM/dt ($M_\odot\ yr^{-1}$)	$(dM/dt)/D^2$ ($10^{-5}\ M_\odot\ yr^{-1}\ kpc^{-2}$)	V_0 ($km\ s^{-1}$)	References
R Aql	M5e–M8e	M	50	2000	0.3	8×10^{-7}	0.89	...	1
RR Aql	M6e–M7e	M	31.5	2400	0.4	4×10^{-7}	0.25	...	2, 3
R Cas	M7e	M	20	1300	0.2	6.6×10^{-7}	1.65	11	4, 5
U CVn	M7e	M	21	3300[a]	...	...	...	...	6
S CrB	M6e–M8e	M	1.5	3300[a]	0.4	4×10^{-6}	2.5	...	1, 5, 6
NML Cyg	M7 I	...	0.5	2000[a]	2.0	6.4×10^{-5}	1.6	23	2, 7, 8
V1057 Cyg	...	...	4	2000	...	...	...	...	
α Her	M5 II	SRc	0	5000[a]	...	9×10^{-8}	...	...	1
U Her	M6.5e–M8e	M	−14	4000[a]	0.3	2.6×10^{-6}	2.89	...	1, 5
R Leo	M6.5e–M9e	M	0	2700[a]	0.3	8.5×10^{-7}	0.94	7	4, 6
R LMi	M7e	M	1.5	2700	0.4	10^{-6}	0.63	6	4
R Lyn	S3e	M	2	4000[a]	...	...			9
R Peg	M7e	M	26	2000	...	...	...	...	9
VX Sgr	M41e–M9a	SRb	0	3000[a]	1.5	...	...	...	6, 10, 11

[a] Sensitivity limited by standing waves.

REFERENCES.—(1) Gehrz and Woolf 1971. (2) Bowers, Johnston, and Spencer 1981. (3) Hyland *et al.* 1972. (4) Knapp *et al.* 1982. (5) Wilson *et al.* 1972. (6) Kukarkin *et al.* 1969. (7) Johnson 1968. (8) Morris and Jura 1983. (9) Becvar 1959. (10) Fawley 1977. (11) Humphreys 1975.

opposite position of the optical axis were subtracted synchronously in the spectrometers. In the difference spectra, the amplitude of the standing wave was ~10 K in 1980 February. The dominant periodicity was ~70 MHz, which corresponds to a reflection path of 7 m, twice the distance between the receiver and the subreflector. In addition, the pattern often appears to be partially modulated by a second sinusoid with half-period of ~100 MHz, which corresponds to the distance between the receiver and a bulkhead port in the telescope cavity through which the beam from the receiver must pass to reach the tertiary flat. While the standing wave pattern consisted mainly of a dual sinusoid, the pattern was not regular enough so that it could be entirely removed by fitting a function. However, the pattern was smooth enough that our sensitivity to narrow (~1 MHz) lines was not significantly degraded. In 1980 August, we reduced the dominant standing wave pattern to about half by gluing to the center of the subreflector a small disk of Eccosorb foam with a diameter equal to the subreflector's image on itself.

The results are presented in Table 1. The first, second, and third columns give the name, spectral type, and variability type of each star observed, taken from Becvar (1959), Gehrz and Woolf (1971), and Kukarkin *et al.* (1969). The fourth column contains the LSR velocity at the center of the spectrometers. The effective velocity coverage, with a resolution of 3 MHz (4.8 $km\ s^{-1}$), was 45 MHz (73 $km\ s^{-1}$) centered on the LSR velocity to which the receiver was tuned. The upper limit to the 183 GHz flux, given in the fifth column, refers to narrow spectral features (~1 $km\ s^{-1}$) which we consider the more likely to be detected (see § III). It corresponds to twice the theoretical rms noise level. From our flat spectra, such as that of V1057 Cyg in Figure 1*b*, we were able to verify that we did obtain a channel-to-channel noise level consistent with our system temperature. Because of the uncertainty in our baselines, we consider this also to be the detection limit for broad spectral features.

We feel that the 2 σ upper limit also applies to narrow features in spectra having poor baselines. Figure 1*a* shows a spectrum of α Her in which such a feature appears to be present. The feature also appeared in the high-resolution digital spectrometer. We cannot be confident that this is a real signal because the observation of this source was hindered by mechanical and tracking problems with the telescope. The spectrum consists of only one left-right pair, of which both parts were terminated early due to loss of tracking. The spectrum has the shortest integration time and the most irregular baseline of all our observations. The amplitude of the feature is only 2–3 σ, depending on where one chooses to draw the baseline. It does illustrate, however, that narrow features could be recognized even in the presence of strong standing waves. No

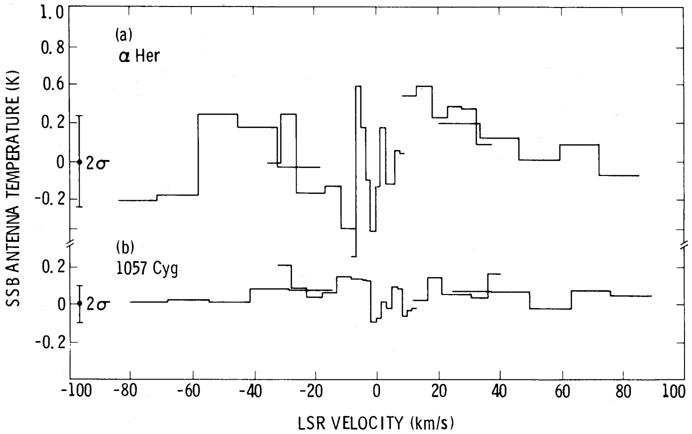

FIG. 1.—(*a*) The spectrum observed in the direction of α Her in the 183 GHz line of water vapor. The central channels are 1 MHz wide; those adjacent, 3 MHz; the outer channels, 8 MHz. The full length of the error bar on the left corresponds to twice the rms noise level for the 1 MHz channels as calculated from the measured system temperature. (*b*) As above for 1057 Cyg.

other narrow features as prominent as the one in the α Her spectrum were observed.

In the spectra with poor baselines, our ability to detect broad spectral features is reduced. Such spectra have been marked with a footnote to the flux upper limit in Table 1.

III. DISCUSSION

In order to assess the significance of the results, we can estimate the intensity of the signals that might be expected.

We consider first possible thermal emission. The flux density from water in local thermodynamic equilibrium in a stellar envelope at a distance D, in a line which has a width of ΔV, may be written as

$$S = \frac{X_{\mathrm{H_2O}}\, N_{\mathrm{env}} f_{3(1,3)}\, Ah\nu}{4\pi D^2(\nu\Delta V/c)}\,, \qquad \text{(1a)}$$

where $X_{\mathrm{H_2O}}$ is the relative abundance of water; N_{env} is the total number of gas molecules in the envelope, $= 6 \times 10^{56}$ times the mass of the envelope in $M_\odot$; $f_{3(1,3)}$ is the number of molecules in the $3_{1,3}$ rotational state of water, and is given in equation (2) of Waters *et al.* (1980); A is the probability of spontaneous emission, $= 3.6 \times 10^{-6}\ \mathrm{s^{-1}}$; and h, ν, and c have their usual meanings. The equation may be conveniently expressed as

$$\left[\frac{S}{\mathrm{Jy}}\right] = 7.4 \times 10^{11} X_{\mathrm{H_2O}} \left[\frac{M_{\mathrm{env}}}{M_\odot}\right]\left[\frac{D}{\mathrm{kpc}}\right]^{-2} \times \left[\frac{\Delta V}{\mathrm{km\ s^{-1}}}\right] T^{-1.5} \exp\left(-\frac{204}{T}\right). \qquad \text{(1b)}$$

The masses of late-type stellar envelopes have been estimated in the range of a few tenths to a few solar masses. The abundance of water is predicted to be almost as high as 10^{-3} because all the available oxygen not bound to carbon is in the form of water (Goldreich and Scoville 1976). However, we could imagine it to be as low as 10^{-6} if interstellar cloud chemistry is typical (e.g., Prasad and Huntress 1980). Adopting an appropriate average temperature presents some difficulty since the temperature in such envelopes varies from $\sim 10^3$ K near the star to a few tens of K, or less, near the outer part of the envelope. The radial dependence is probably steeper than inverse square root in the inner envelope because of absorption by dust in the envelope. We will adopt a temperature of 100 K because the emissivity of the 183 GHz line is not a strong function of temperature, until the temperature drops below 60 K (see Fig. 2 in Waters *et al.* 1980). The flux density from 183 GHz line emission can then be expressed as

$$S(\mathrm{LTE,\ max}) = 3200\left[\frac{M_{\mathrm{env}}}{M_\odot}\right]\left[\frac{\mathrm{kpc}}{D}\right]^2 \times \left[\frac{X(\mathrm{H_2O})}{10^{-3}}\right]\left[\frac{30\ \mathrm{km\ s^{-1}}}{\Delta V}\right] \mathrm{Jy}\,. \qquad \text{(2a)}$$

Assuming the lifetime of the outflow to be $\sim 10^4$ yr (Knapp *et al.* 1982), we can estimate the mass of the envelope from the mass-loss rate and can write the equation as

$$S(\mathrm{LTE,\ max}) = 320\left[\frac{dM/dt}{10^{-5}\ M_\odot\ \mathrm{yr^{-1}}}\right]\left[\frac{\mathrm{kpc}}{D}\right]^2\left[\frac{X(\mathrm{H_2O})}{10^{-3}}\right] \times \left[\frac{30\ \mathrm{km\ s^{-1}}}{\Delta V}\right] \mathrm{Jy}\,. \qquad \text{(2b)}$$

This level of thermal emission, however, cannot be expected when one considers the density requirement for collisional excitation. Collision rates have been calculated by Green (1980) to be in the range of 10^{-12} to $10^{-11}\ \mathrm{cm^3\ s^{-1}}$ for the 3_{13} and 2_{20} levels over a wide range of temperatures. The probabilities of spontaneous emission via the most probable pathways are $0.13\ \mathrm{s^{-1}}$ and $0.27\ \mathrm{s^{-1}}$, respectively, for these levels. Thus, if the stellar envelopes were optically thin in these transitions, densities on the order of $10^{10}\ \mathrm{cm^{-3}}$ would be required for collisional exictation to maintain the level populations against spontaneous decay. The density requirement is reduced if the emitted photons are reabsorbed by the envelope, since only photons which escape from the envelope cause a net deexcitation. This trapping cannot be very significant, however, since the expansion of the envelope causes most potentially absorbing molecules to be Doppler shifted away from the rest velocity in the frame of the emitting molecules. The radial density dependence of a uniform mass loss may be expressed as

$$n(\mathrm{H_2}) = 1.5 \times 10^9 \left[\frac{dM/dt}{10^{-5}\ M_\odot\ \mathrm{yr^{-1}}}\right]\left[\frac{10^{14}\ \mathrm{cm}}{r}\right]^2 \mathrm{cm^{-3}}\,. \qquad \text{(3)}$$

Thus, we see that collisional excitation can be expected to occur only within a few stellar radii (a few times 10^{14} cm) of the surface for a mass loss of $10^{-5}\ M_\odot\ \mathrm{yr^{-1}}$. Since, in a uniform outflow, the mass fraction interior to a given radius depends linearly on the radius, and since envelopes may extend to a few $\times 10^{16}$ cm, we can only expect the few inner percent, or less, of the envelope to emit thermal 183 GHz emission. The intensity of the line from the region is also reduced by the temperature-dependent factor (see eq. [1b]) because the inner core of the envelope has a temperature of ~ 1000 K. In the sixth column of Table 1, we have listed the distances of the stars, taken from Bowers, Johnston, and Spencer (1981), Humphreys (1975), Knapp *et al.* (1982), Morris and Jura (1983), and Wilson *et al.* (1972). In the seventh column we have tabulated estimates of the mass-loss rate, taken from Bowers, Johnston, and Spencer (1981), Gehrz and Woolf (1971), Knapp *et al.* (1982), and Morris and Jura (1983). From these we have calculated, and tabulated in the eighth column, the factor $(dM/dt)D^{-2}$ in convenient units to facilitate comparison of the measured flux limits with equation (2b). To allow for the expected line width in equation 2b, we have also tabulated, in the ninth column, the outflow velocity, taken from Bowers, Johnston, and Spencer (1981) and Knapp *et al.* (1982). It is clear that the present observations are about three orders of magnitude too insensitive to detect thermal 183 GHz water emission from these stellar envelopes.

Deguchi (1977) has modeled the excitation of water in the inner envelope of a prototypical mass-loss star, in the range between one and two stellar radii (assumed to be 6×10^{13} cm). The velocity was assumed to be proportional to the distance from the surface of the star, the temperature dependence inverse square-root, and the mass-loss rate to be $10^{-5}\ M_\odot\ \mathrm{yr^{-1}}$. He computed a 183 GHz maser power of 1.3×10^{43} photons $\mathrm{s^{-1}}$. Scaling his result to the mass-loss rate, it corresponds to a flux at Earth of

$$S_{183} = 23\left[\frac{dM/dt}{10^{-5}\ M_\odot\ \mathrm{yr^{-1}}}\right]\left[\frac{\mathrm{kpc}}{D}\right]^2\left[\frac{\mathrm{km\ s^{-1}}}{\Delta V}\right] \mathrm{Jy}\,. \qquad \text{(4)}$$

In Deguchi's velocity model, the amplification occurs in the acceleration region so that velocity coherence occurs only where the flow is perpendicular to the line of sight. Thus, the power may be expected to be confined to a thermal line width of 1 MHz ($=1.6$ km s^{-1} at 1000 K) centered at the LSR velocity of the star. For a star at 0.2 kpc with a mass-loss rate of 10^{-5} $M_\odot$ yr^{-1}, the expected flux would be 360 Jy. Thus, the flux from Deguchi's model star at 200 pc distance would lie about an order of magnitude below our detection level. Scaling from Deguchi's model, the stars observed should have emission about two orders of magnitude weaker than our detection level.

The possibility that some stars may have intense maser emission well in excess of Deguchi's model, and potentially detectable by us, cannot be ruled out on the basis of our limited survey which sampled only 13% of the known 22 GHz water maser stars (Kleinmann, Dickinson, and Sargent 1978).

Prospects for future searches should be quite good. With current technology, a Schottky diode system with 400 K SSB system temperature is possible at 183 GHz. An SIS receiver might achieve half that, giving an order of magnitude better sensitivity than the search reported here. Careful attention will need to be paid to reducing standing waves in the telescope system. Path-length modulator (e.g., a reciprocating mirror; Gustincic 1977) has been found to be effective in canceling the effects of reflected radiation (Payne 1983). Another order of magnitude improvement in sensitivity can be achieved by using a 3 m balloon-borne telescope (Hoffmann, Fazio, and Harper 1983; Melchiorri 1983). A combination of these two advances will permit us to detect or put useful limits on 183 GHz maser emission from later-type stars. Eventually, large orbiting telescopes such as FIRST (Olthof 1983) and LDR (Swanson *et al.* 1983) should permit the detection of thermal 183 GHz line emission from water in stellar envelopes.

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D. F. DICKINSON: Lockheed Palo Alto Research Laboratory, 3251 Hanover Street, Palo Alto, CA 94304

T. B. H. KUIPER, P. N. SWANSON, and P. ZIMMERMANN: Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109

E. N. RODRIGUEZ KUIPER: Hewlett-Packard, 5400 West Rosecrans, Lawndale, CA 90260