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WATER EMISSION FROM INFRARED STARS

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ABSTRACT

Twenty-two new infrared stars with microwave water-vapor emission have been found, all but four of which are optically identified long-period variables. They are heavily reddened, late M stars that commonly show time variations. Hydroxyl emission is present in all but a few instances. Excited-state SiO emission is seen in many H_2O–infrared stars (although about half have not yet been checked). Those that are Mira variables always have a visual change of more than 6 mag during their light cycle. Other optical and infrared properties are discussed.

Subject headings: infrared: sources — molecular processes — stars: long-period variables

I. INTRODUCTION

Water vapor was first observed in infrared stars at radio frequencies by Knowles *et al.* (1969) and, subsequently, by Schwartz and Barrett (1970), Turner *et al.* (1970), and Dickinson *et al.* (1973). In each experiment, the line observed was the 6_{16}–5_{23} rotational transition at 22235.080 MHz. Those water-emission stars with optical identification, without exception, are long-period variables, typically Miras, but not infrequently semiregular variables. All these stars are in the final stages of stellar life, having evolved from the main sequence onto the giant branch; they are losing mass and have dusty envelopes, as evidenced by their large $I - K$ color index (0.8–2.2 μ). It is from this circumstellar atmosphere of gas and dust that water vapor and OH emission arise.

Recently, maser emission from silicon monoxide was found in the atmosphere of many of these H_2O–infrared stars (cf. Buhl *et al.* 1974; Thaddeus *et al.* 1974). The SiO lines arise from rotational transitions in excited vibrational states of the molecule. Velocities for SiO emission are close to those for H_2O, suggesting that they all arise from the same general region of the stellar atmosphere. This, coupled with the strong maser character of the SiO emission, has heightened interest in the long-period variables with radio-frequency H_2O and SiO.

In order to characterize these stars better, we have undertaken a survey of infrared stars, drawn principally from the Caltech *Two-Micron Sky Survey* (Neugebauer and Leighton 1969). In all, about 228 stars were searched, resulting in the detection of 22 new water sources.

II. OBSERVATIONS

The development of the K-band maser at the Haystack Observatory[1] has made possible the order-of-magnitude improvement in sensitivity of these observations. Previous work used a mixer front end with a single-sideband noise figure of about 2000 K. The maser, by contrast, typically runs about 150 K, the precise figure being affected by atmospheric water-vapor content and the wetness of the radome that covers the 120 foot (37 m) parabolic antenna on which the measurements were made.

Spectral information was provided by a 100-channel autocorrelator. Searches were made with a channel resolution of 2.2 km s^{-1} and a total bandwidth that covered about 80 km s^{-1}. The velocity error for this resolution is approximately 0.6 km s^{-1}. This resolution is nearly ideal for water-line searches because line widths in infrared stars are typically very close to this figure. In a few cases, the lines may be underresolved and some intensity dilution may result. For three stars, where line widths were obviously very narrow, we used a narrower channel width. Time limitations of the search program prevented us, however, from obtaining high-resolution profiles in general. Radial-velocity information for individual stars was obtained from the *Bibliography of Stellar Radial Velocities* (Abt and Biggs 1972) or, where known, from OH observations. If no velocities were available, stars were usually searched from approximately -75 to $+75$ km s^{-1}. Upper limits for stars without H_2O varied, but they were typically 5 or 6 Jy (peak-to-peak). One degree of antenna temperature is about 19 Jy.

Observations were made in the total-power mode, with each run consisting of 5 minutes off-source followed by 5 minutes on-source. For detection, a star had to be seen on at least two runs. Spectra were corrected for antenna gain as a function of elevation and for atmospheric water-vapor content as a function of elevation and humidity. The fractional error in the temperature varies as $\Delta\tau/\sin$ el, where $\Delta\tau$ is the error in the water-vapor optical depth and the denominator is the sine of the elevation angle. Since $\Delta\tau$ is probably always less than 0.1, the total error, including pointing and calibration, is typically less than 20 percent but may be as poor as 50 percent at extremely low elevations ($<10°$).

[1] Radio astronomy programs at the Haystack Observatory are conducted with support from the National Science Foundation, grant GP-25865.

TABLE 1

NEW INFRARED WATER-VAPOR STARS

Name	IRC Number	T_{ant} (K)	Radial Velocity (km s^{-1})	ΔV (km s^{-1})	Observation Date
Y Cas...........	+60001	0.20	+2.4	2.4	1974 August 5
CIT 3............	+10011	0.35	+22.2	3.2	1973 September 9
o Cet............	+00030	0.50	+46.7	2.8	1973 September 10
S Per............	+60088	2.25 (5.60)	−45.2	~2	1973 March 29 (November 23)
		2.75 (5.60)	−37.6	3.6	
		0.44 (0.75)	−31.2	~2	
		0.57 (0.60)	−27.5	~3	
W Eri............	−30033	2.60	0.0	~4	1974 August 5
R Tau...........	+10060	0.40	+11.2	2.8	1973 September 10
Z Pup...........	−20133	1.80	+4.5	2.6	1974 September 2
R Leo...........	+10215	0.40	−1.0	2.5	1973 September 10
V Ant...........	...	1.05	−18.2	3.0	1973 March 30
U CVn...........	+40238	0.45	−23.0	2.8	1973 March 30
RT Vir...........	+10262	0.85	+15.1	2.8	1973 March 30
WX Ser..........	+20281	0.80	+7.7	< 2	1974 August 5
	+30292	0.75	+46.3	2.8	1974 December 13
	+10365	2.25	−40.3	0.7	1974 September 1
	−20540	3.05	+10.9	3.3	1974 November 23
RT Aql..........	+10433	1.75	−29.6	1.5	1974 September 1
Z Cyg...........	+50314	1.55	+1.3	1.3	1974 September 2
SY Aql..........	+10450	0.70	−48.5	2.4	1974 September 2
UX Cyg..........	+30464	0.20	+2.1	2.5	1973 September 9
TW Peg..........	+30481	37.60 (15.80)	−7.8	2.2	1973 January 12 (March 30)
		~0.30	−18.5	~2	1974 December 11
SV Peg..........	+40501	3.10	+1.9	2.5	1974 August 5
PZ Cas..........	+60417	0.25	−46.6	~4	1974 December 12
		0.25	−40.0	~4	

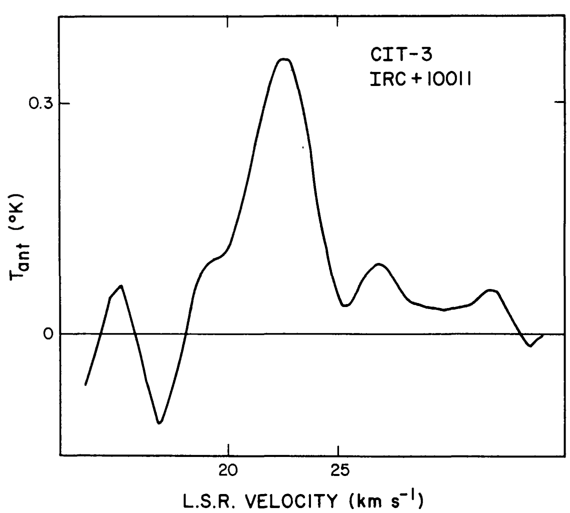

FIG. 1.—Water-vapor spectrum of IRC+10011. The central star here is a Mira variable with a photospheric temperature near 2000 K. Zappala *et al.* (1974) have measured the diameter of this object at 2.2, 10, and 20 μ by lunar occultations. Their 10 μ data suggest thermal emission from a dust shell 0".135 in diameter at a temperature of 540 K. IRC+10011 is highly reddened, with an $I - K$ color index of 7.60.

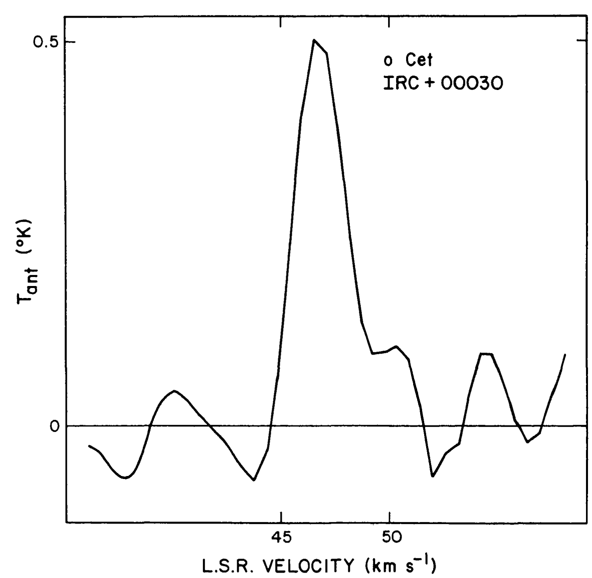

FIG. 2.—Water-vapor spectrum of o Cet. This star revealed a 10 Jy signal on 1973 September 10; observations on 1974 December 12 were negative, less than 7 Jy peak-to-peak. Brightest of all the H_2O stars visually, its maximum magnitude is 2.0. First discovered by Fabricius in 1596, this is Mira, the prototype for variables of this class. A 1665 MHz OH emission line was detected at the Onsala Space Observatory in mid-1974 (Dickinson *et al.* 1975).

TABLE 2

A CATALOG OF INFRARED WATER-VAPOR STARS

Name	IRC	α (1950)	δ (1950)	K	I − K	m_p	OH*	SiO*	Notes†
Y Cas.....	+60001	00h00m45s	+55°24′21″	+1.27	+5.39	8.9– 15.3	Yes, 1	...	M, M6–M8
CIT 3......	+10011	01 03 49	+12 18 42	+1.63	+7.60	...	Yes, 2	...	M
o Cet......	+00030	02 16 49	−03 12 12	...	...	2.0– 10.1	Yes, 3	Yes, 4, 5	M, Mira, M5–M9
S Per......	+60088	02 19 16	+58 21 30	+1.31	+4.39	7.9– 11.1	Yes, 6	No, 4	SR, M3
IK Tau....	+10050	03 50 46	+11 15 42	−1.24	+6.78	11.9– 16.5	Yes, 7	Yes, 4	SR, NML Tau
W Eri......	−30033	04 09 26	−25 15 26	+1.89	+5.20	7.5– 14.5	Yes, 1	...	M, M7
R Tau.....	+10060	04 25 36	+10 03 30	+1.15	+3.92	8.1– 14.7	No, 3	No, 4	M, M6
R Dor.....	...	04 36 10	−62 10 30	...	...	5.9– 6.9	...	...	SR, M7, see ref. 18
U Ori......	+20127	05 52 51	+20 10 24	−0.49	+5.40	5.3– 12.6	Yes, 8	Yes, 9	M, M8
L_2 Pup....	...	07 12 01	−44 33 21	...	...	2.6– 6.0	...	...	SR, M5, see ref. 18
VY CMa...	−30087	07 20 53	−25 40 24	−0.69	+5.56	10.0– 10.9	Yes, 10	Yes, 4, 5	Irr, M3
Z Pup.....	−20133	07 30 29	−20 32 49	+1.77	+5.71	7.2– 14.6	Yes, 11	...	M, M4–M9
X Hya.....	...	09 33 07	−14 28 00	...	...	8.0– 13.6	...	...	M, M7, see ref. 18
R LMi.....	+30215	09 42 35	+34 44 18	−0.62	+4.22	6.3– 13.2	Yes, 12	Yes, 9	M, M7–M8
R Leo.....	+10215	09 44 52	+11 39 48	...	...	4.4– 11.3	Yes, 11	Yes, 4, 5	M, M6.5–M9
V Ant.....	...	10 18 55	−34 32 30	...	...	9.2–(12.5	Yes, 6	...	M, M7
R Crt......	−20222	10 58 09	−18 03 36	−1.23	+4.81	9.8– 11.2	Yes, 13	...	SR, M8
U CVn.....	+40238	12 44 57	+38 38 24	+2.84	+5.10	8.8–(12.5	Yes, 1, 6	No, 4	M, M7
RT Vir.....	+10262	13 00 05	+05 27 06	−0.97	+4.38	9.0– 10.3	Yes, 3	Yes, 9	SR, M8
W Hya.....	−30207	13 46 13	−28 07 06	...	...	7.7– 11.6	Yes, 8	Yes, 4, 5, 9, 14	SR, M8
RU Hya...	−30215	14 08 42	−28 38 24	+1.56	+3.78	7.2– 14.3	Yes, 12	...	M, M6
RX Boo....	+30257	14 21 58	+25 55 54	−1.85	+4.62	8.6– 11.3	No, 2, 13	Yes, 9	SR, M8
RS Vir.....	+00243	14 24 45	+04 53 54	+1.48	+4.96	7.0– 14.4	Yes, 11	...	M, M6–M7
S CrB......	+30272	15 19 19	+31 32 36	−0.20	+3.87	6.5– 14.0	Yes, 8	Yes, 4	M, M7
WX Ser....	+20281	15 25 32	+19 44 06	+1.94	+6.08	12.0–(16	Yes, 2	Yes, 4	M, M8
U Her.....	+20298	16 23 35	+19 00 24	−0.31	+4.18	6.5– 13.4	Yes, 8	Yes, 4	M, M7
...	+30292	16 25 59	+34 54 36	+3.10	+6.34	...	Yes, 2	...	...
AH Sco....	...	17 08 03	−32 16 00	...	...	8.1– 12.0	...	...	SR, M3, see ref. 18
...	−20424	18 00 58	−20 19 12	+0.90	+6.31	...	Yes, 2	...	...
VX Sgr....	−20431	18 05 05	−22 14 00	−0.37	+4.76	7.5– 11.8	Yes, 15	Yes, 4	SR, M4
...	+10365	18 34 59	+10 23 00	+0.77	+6.08	...	Yes, 2	...	...
OH 30.1–0.7	...	18 46 04.8	−02 53 36	...	...	...	Yes, 16	...	See ref. 16
OH 32.8–0.3	...	18 49 47.5	−00 17 42	...	...	...	Yes, 16	...	See ref. 16
R Aql	+10406	19 03 58	+08 09 06	−0.57	+5.04	5.7– 12.0	Yes, 2	Yes, 4	M, M7
...	−20540	19 05 56	−22 19 12	+2.22	+6.05	...	Yes, 2	...	...
RT Aql....	+10433	19 35 36	+11 36 16	+1.40	+5.14	7.8– 14.5	No, 3	...	M, M6–M8
RR Aql....	+00458	19 54 58	−02 01 12	+0.66	+4.73	7.8– 14.5	Yes, 2	Yes, 4	M, M7
Z Cyg.....	+50314	20 00 00	+49 54 06	+2.44	...	7.6– 14.7	Yes, 3	...	M, M5–M6
SY Aql....	+10450	20 04 43	+12 48 10	+2.70	+5.09	8.3– 15.4	Yes, 3	...	M, M5
...	+40448	20 44 33	+39 56 06	+0.62	+8.17	...	Yes, 7	Yes, 4	NML Cyg
UX Cyg....	+30464	20 53 00	+30 13 24	+1.69	+5.23	9.0– 16.5	Yes, 2, 3	No, 4	M, M4–M6
TW Peg....	+30481	22 01 41	+28 06 30	−0.63	+3.98	7.0– 9.2	Yes, 6	No, 4	SR, M3
SV Peg.....	+40501	22 14 31	+35 06 39	−0.55	+4.45	9.4– 11.0	...	...	SR, M7
R Peg......	+10527	23 04 08	+10 16 22	+0.33	+4.28	7.1– 13.8	Yes, 12	...	M, M7
PZ Cas....	+60417	23 41 41	+61 31 00	+0.98	+4.18	9.8– 12.7	...	...	SR, M3
R Cas.....	+50484	23 55 53	+51 06 36	−1.84	+4.86	5.5– 13.0	Yes, 17	Yes, 4	M, M7

NOTE.—Left parenthesis on stellar magnitude indicates upper limit.

* References: 1, Pataki 1973; 2, Wilson and Barrett 1972; 3, Dickinson *et al.* 1975; 4, Snyder and Buhl 1975; 5, Buhl *et al.* 1974; 6, Dickinson and Chaisson 1973; 7, Wilson *et al.* 1970; 8, Wilson *et al.* 1972; 9, Spencer and Schwartz 1975; 10, Eliasson and Bartlett 1969; 11, Fillit *et al.* 1973; 12, Fillit *et al.* 1972; 13, Bechis 1973; 14, Thaddeus *et al.* 1974; 15, Caswell and Robinson 1971; 16, Observed by the Onsala Space Observatory group of Chalmers University of Technology, Göteborg, Sweden (Yngvesson 1974); 17, Turner and Rubin 1971; 18, after submission of this paper, these stars were detected by J. R. D. Lepine, M. H. Paes de Barros, and R. H. Gammon of the radio astronomy group at Universidade Mackenzie, São Paulo, Brazil.

† M = Mira variable, SR = semiregular variable, Irr = irregular variable; alternate names and spectral type are also given.

Positions were taken from the *Two-Micron Sky Survey* or from the *General Catalogue of Variable Stars* (Kukarkin *et al.* 1969). Positions from the latter reference have been processed here to epoch 1950 for uniformity of presentation.

III. RESULTS

Table 1 lists the new stellar water-vapor sources found in this work. The columns give the star name, the Infrared Catalog (IRC) number from Neugebauer and Leighton (1969), the corrected antenna temperature, the radial velocity, and the line width ΔV. Positions and optical and infrared data are given in Table 2, a general catalog of H_2O–infrared stars. (Appendix A lists stars searched but not detected.) Figures 1–22 present the water-vapor spectra for the new detections. Details on each star are given in the figure legends.

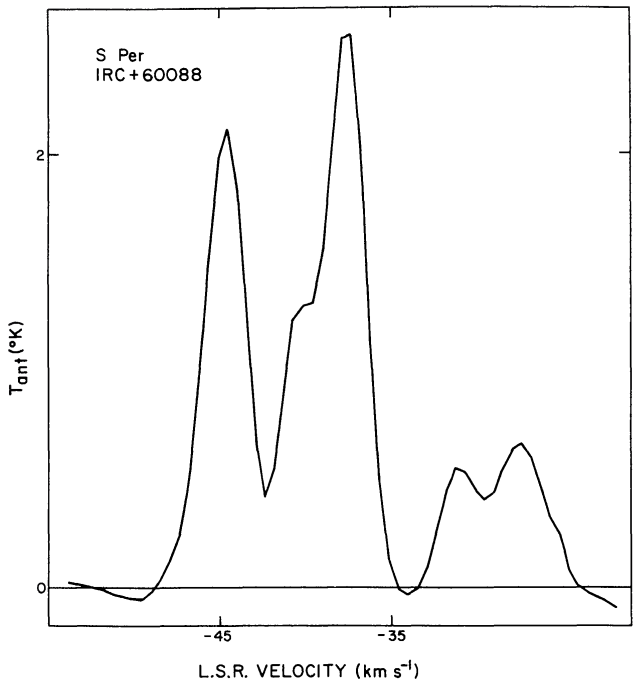

FIG. 3.—Water-vapor spectrum of S Per. S Per is a rather strong H_2O source whose spectrum has at least five emission features (Dickinson 1973). (Multiple lines seem to be characteristic of supergiants like this, VX Sgr, and VY CMa.) On 1973 March 29, the peak feature near -37.5 km s^{-1} was 59 Jy, and by 1974 November 23, it was 106 Jy and the emission at -45.5 km s^{-1} was of comparable intensity. S Per is a semiregular variable with a period of 600–700 days (American Association of Variable Star Observers 1974). Independently detected in water vapor by Baudry and Welch (1974), OH was found at 1612 MHz in S Per by Bowers (1975) and by Dickinson *et al.* (1975).

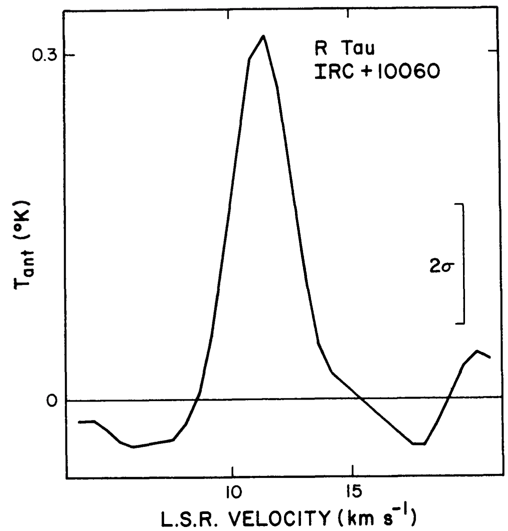

FIG. 5.—Water-vapor spectrum of R Tau. R Tau is one of five stars that do not show OH. Observations at the Onsala Space Observatory were negative to less than 0.6 Jy at 1612 and 1667 MHz despite optical and infrared characteristics that closely resemble other OH–H_2O stars. The weak H_2O emission ($\sim$8 Jy) suggests that this may be only a sensitivity problem. R Tau was also near minimum light during the OH search.

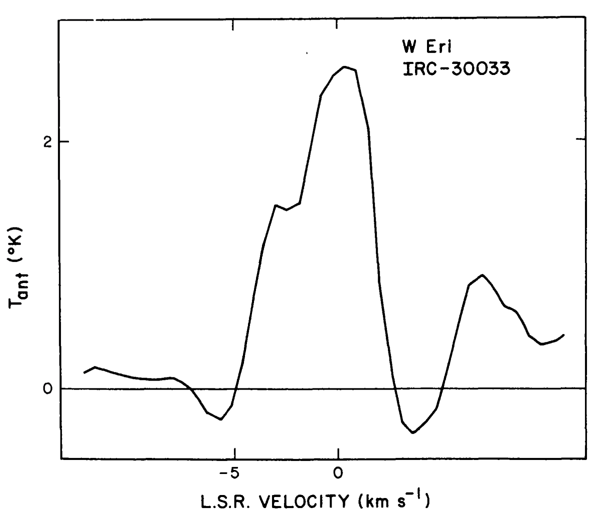

FIG. 4.—Water-vapor spectrum of W Eri. This is a single-feature H_2O source of approximately 49 Jy. Pataki (1973) discovered OH emission in both main lines.

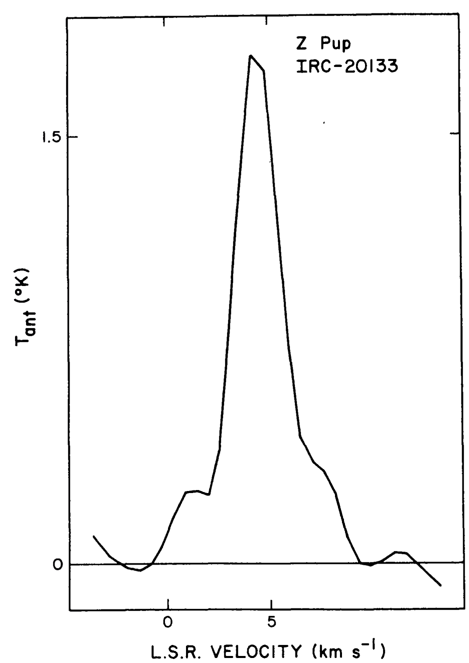

FIG. 6.—Water-vapor spectrum of Z Pup. Substantial variation in spectral type, from M4 to M9, occurs in this star. OH emission was found in Z Pup by Fillit *et al.* (1973) in the main lines.

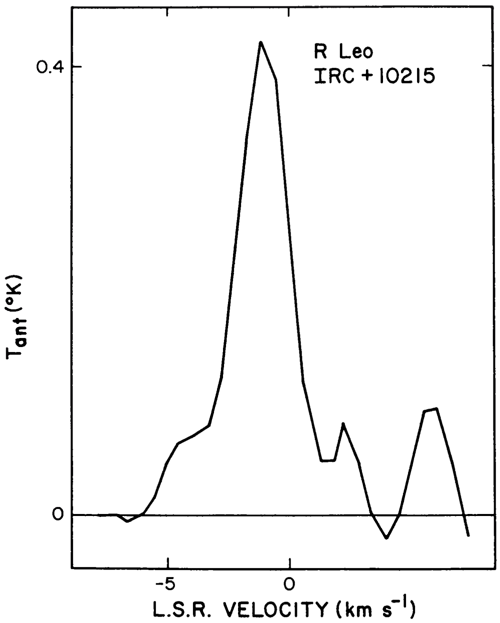

FIG. 7.—Water-vapor spectrum of R Leo. In this bright Mira variable (4.4 mag at maximum), Fillit *et al.* (1973) detected both main lines in OH.

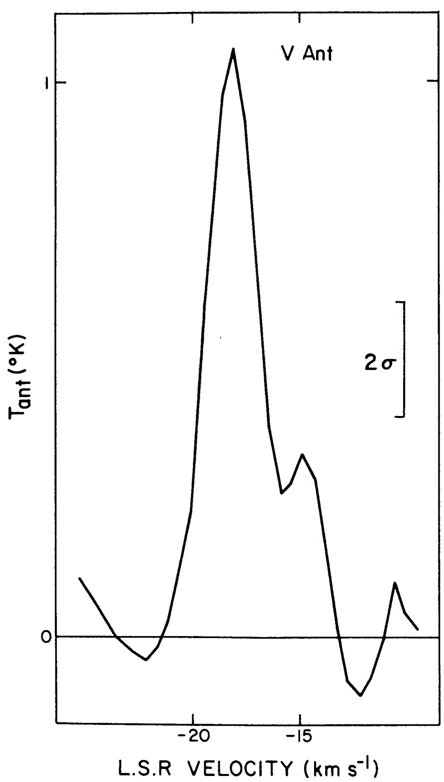

FIG. 8.—Water-vapor spectrum of V Ant. This Mira variable has no IRC identification, its declination being below the survey limits. It is a 1612 MHz OH source (Dickinson and Chaisson 1973).

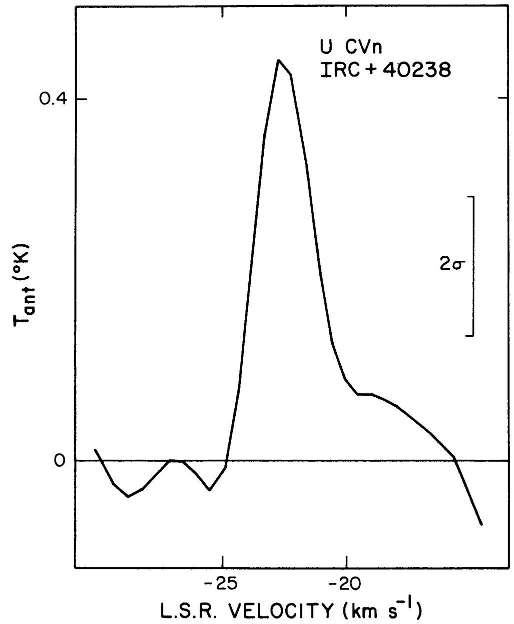

FIG. 9.—Water-vapor spectrum of U CVn. The K magnitude of 2.84 in this Mira variable is one of the lowest apparent infrared luminosities detected in H_2O. Pataki (1973) found main-line OH emission in U CVn, and Dickinson and Chaisson (1973) detected this star at 1612 MHz.

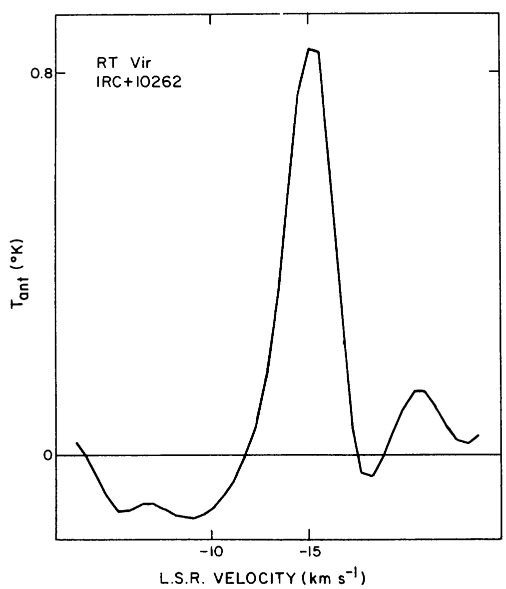

FIG. 10.—Water-vapor spectrum of RT Vir. This short-period (155 day), semiregular variable is negative in OH despite searches to less than 1 Jy in both main lines and at 1612 MHz (Dickinson *et al.* 1975). No phase information was available on RT Vir, since the OH search was made during an unknown point in its light curve.

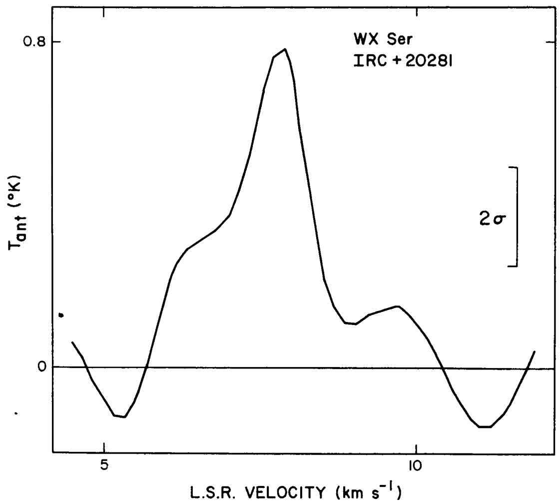

FIG. 11.—Water-vapor spectrum of WX Ser. The least visually intense of all the H_2O stars, WX Ser has a maximum of only 12 mag. The K magnitude is low (1.94), but not excessively so, suggesting again that the infrared flux is the primary factor in producing the H_2O maser. High-resolution observations (0.67 km s^{-1}) revealed only one very narrow feature, ~1 km s^{-1} wide.

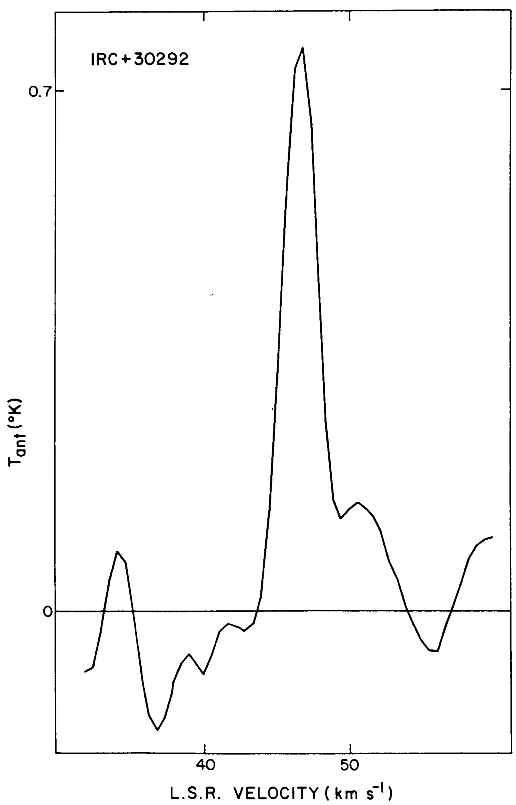

FIG. 12.—Water-vapor spectrum of IRC+30292. This infrared source has a K magnitude of 3.10, and is thus one of the dimmest infrared stars yet detected in the water line. It has no known optical counterpart. On 1973 November 30, it showed no signal to 7 Jy (peak-to-peak); by 1974 December 13, the signal had risen to ~15 Jy.

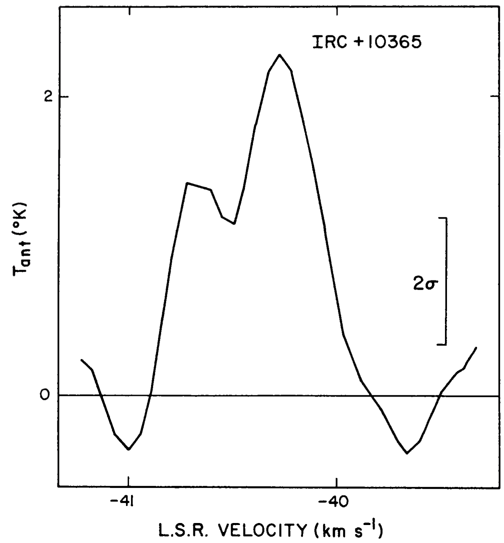

FIG. 13.—Water-vapor spectrum of IRC+10365. Marginally detected on 1973 December 8 (~9 Jy), the signal was approximately 17 Jy on 1974 September 1, both spectra having been taken with a resolution of 2.2 km s^{-1}. Subsequent observations on September 1 with 0.22 km s^{-1} resolution revealed the feature to be underresolved with the wider resolution and, actually, just over 40 Jy with a width of about 0.75 km s^{-1}.

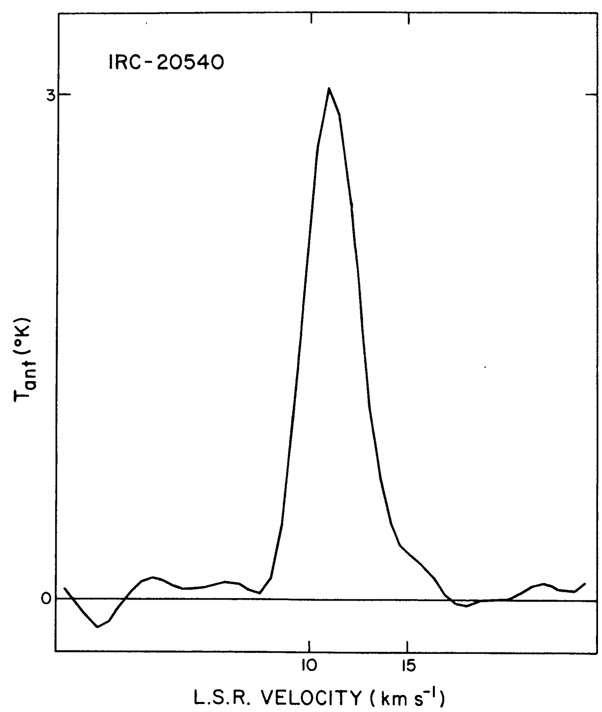

FIG. 14.—Water-vapor spectrum of IRC−20540. Low-elevation observations on 1973 December 8 revealed a marginal line of about 15 Jy; on 1974 November 23, the strength was about 60 Jy.

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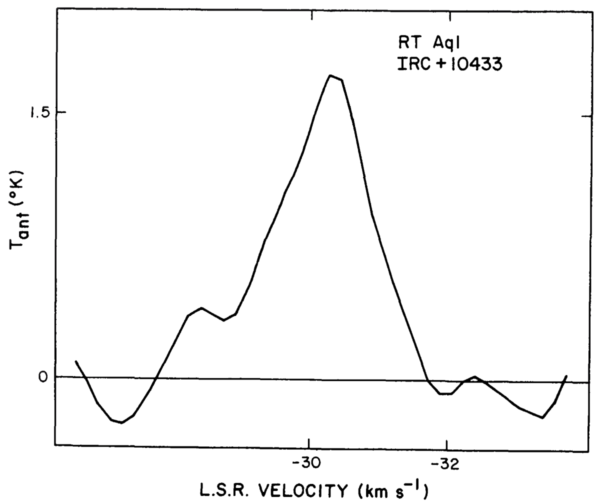

FIG. 15.—Water-vapor spectrum of RT Aql. OH emission has been searched for in this star at 1612 MHz to less than 0.7 Jy (peak-to-peak) (Dickinson *et al.* 1975). RT Aql went through its light minimum on 1974 June 6, just before the OH search.

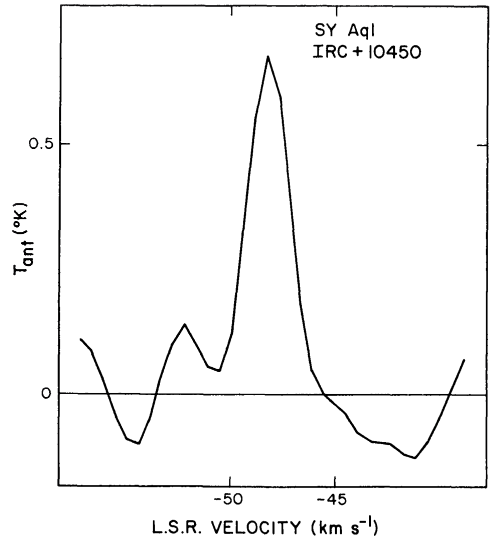

FIG. 17.—Water-vapor spectrum of SY Aql. Observations on 1974 August 5 showed a possible signal at a level of ~8 Jy. The confirmation attempt on 1974 September 2 showed a definite signal of 13 Jy. SY Aql was detected at 1612 MHz in OH in the same experiment with Z Cyg.

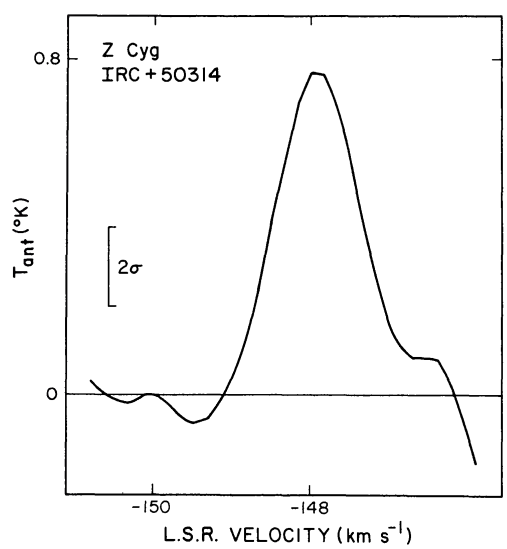

FIG. 16.—Water-vapor spectrum of Z Cyg. Z Cyg is a relatively short-period Mira (264 days) and has the highest peculiar velocity of any H_2O star observed—about -148 km s^{-1}. OH was observed at 1612 MHz by Dickinson *et al.* (1975).

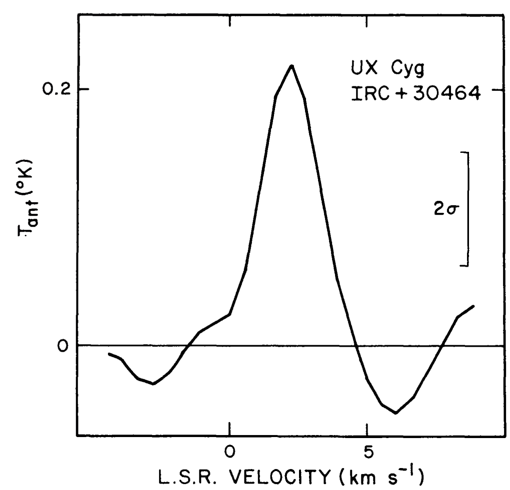

FIG. 18.—Water-vapor spectrum of UX Cyg. This is a very weak H_2O source, about 4 Jy.

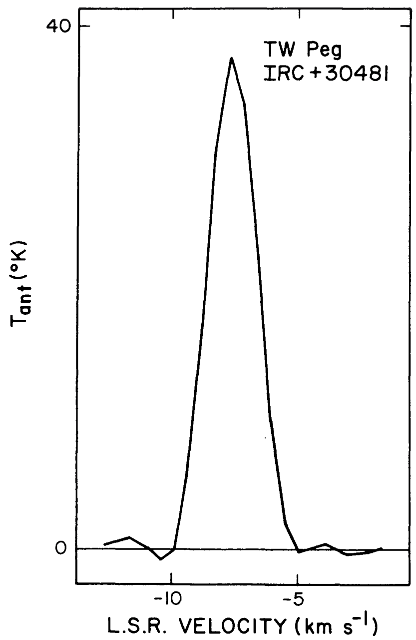

FIG. 19.—Water-vapor spectrum of TW Peg. This extraordinary star had a water line of 715 Jy on 1973 January 12, making it the strongest H_2O–infrared star after VY CMa. By 1973 March 30, it had decreased to 300 Jy (since its visual light also diminished), and on 1974 December 11, the major feature at -7.8 km s^{-1} had disappeared and a secondary one of about 7 Jy appeared at -18.5 km s^{-1}. TW Peg has the longest period of any water star known, 956 days.

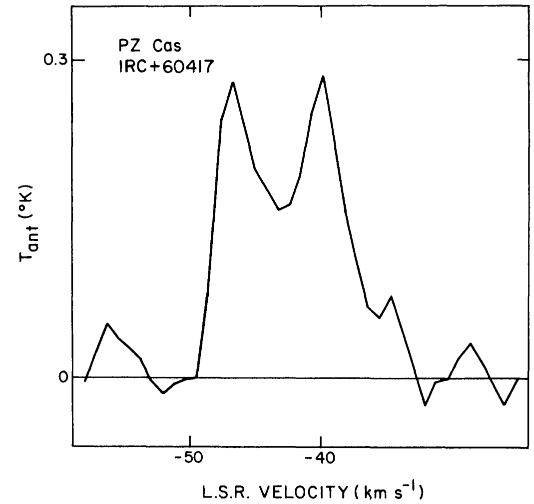

FIG. 21.—Water-vapor spectrum of PZ Cas. A long-period supergiant (900 days), PZ Cas was marginally detected on 1973 March 29 with an intensity of ~ 3 Jy. The feature (at -46.6 km s^{-1}) had increased to 5 Jy by 1974 December 12, and a second feature of comparable intensity had appeared at -40.0 km s^{-1}.

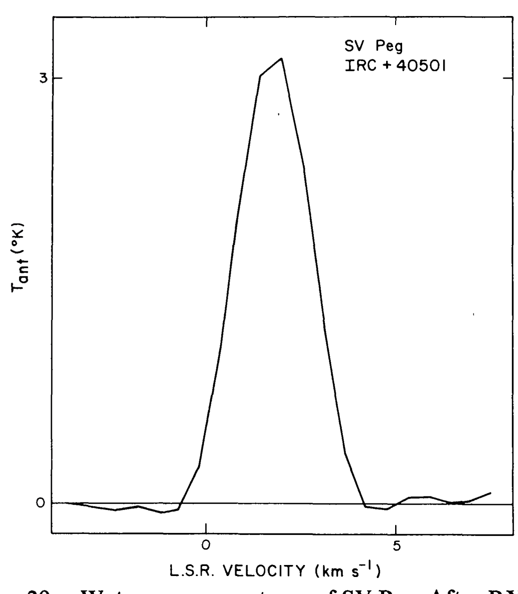

FIG. 20.—Water-vapor spectrum of SV Peg. After RX Boo, this semiregular variable has the shortest period, 145 days. It has not yet been searched for OH emission.

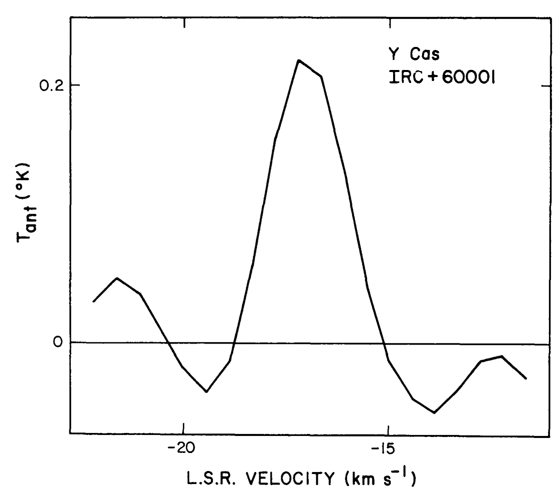

FIG. 22.—Water-vapor spectrum of Y Cas. Pataki (1973) detected this 4 Jy water source in OH in the main lines.

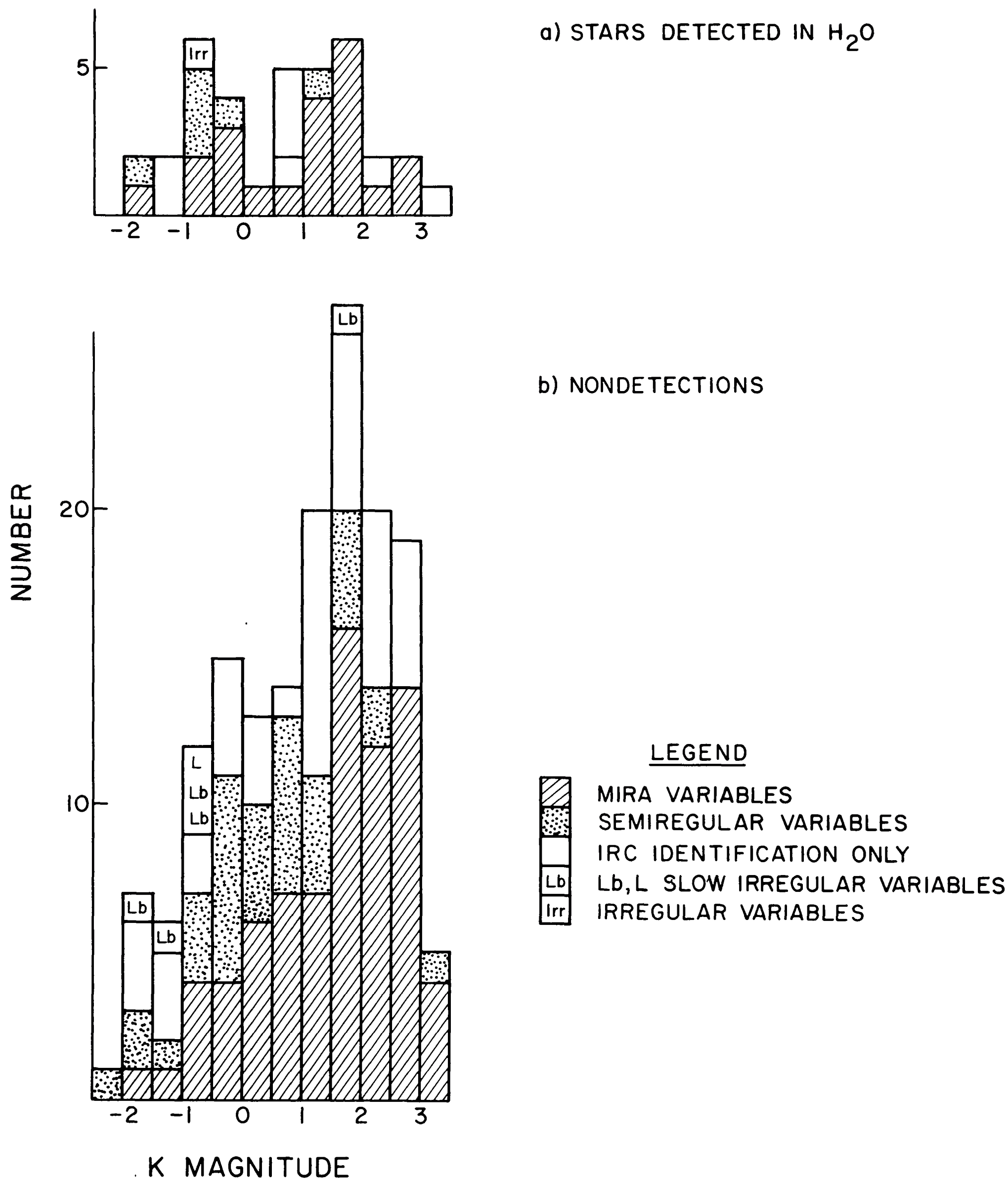

FIG. 23.—Histogram as a function of K magnitude: (*a*) stars detected in H_2O; (*b*) stars for which H_2O was not found

IV. DISCUSSION

Prominent characteristics of the infrared water stars can be summarized as follows:

1. To the extent that these stars are similar to one another, one might expect detectability to be strongly coupled to the apparent magnitude. (That is to say, brighter stars would be closer.) But Figure 23*a* shows that detectability is only weakly correlated with the K magnitude. Figure 23*a* is a histogram of H_2O stars as a function of K magnitude (where known), and Figure 23*b* shows those stars for which H_2O was not found. The number of H_2O stars found is not heavily coupled to the infrared flux, suggesting that the maser intensity is not strongly correlated with the intrinsic brightness of the star. This is borne out in the visual range as well. Figures 24*a* and 24*b* show a similar plot for maximum visual magnitude; once again, the detection of water-emission stars is only slightly greater for the smaller values of m_p.

2. The H_2O–infrared stars show substantial reddening, where measured; all have $I - K$ color indices greater than 3.78 (Figs. 25*a* and 25*b*). The falloff with increasing $I - K$ seems to reflect only that fewer sources were examined in this region. The near-infrared is suspected to provide the pump flux for the OH and H_2O masers (cf. Litvak 1969; Litvak and Dickinson 1972); the reddened nature of these stars lends strength to this idea.

3. Those H_2O–infrared stars that are Mira variables all exhibit a differential change in the visual of greater than 6.3 mag (Fig. 26). Miras as a group typically

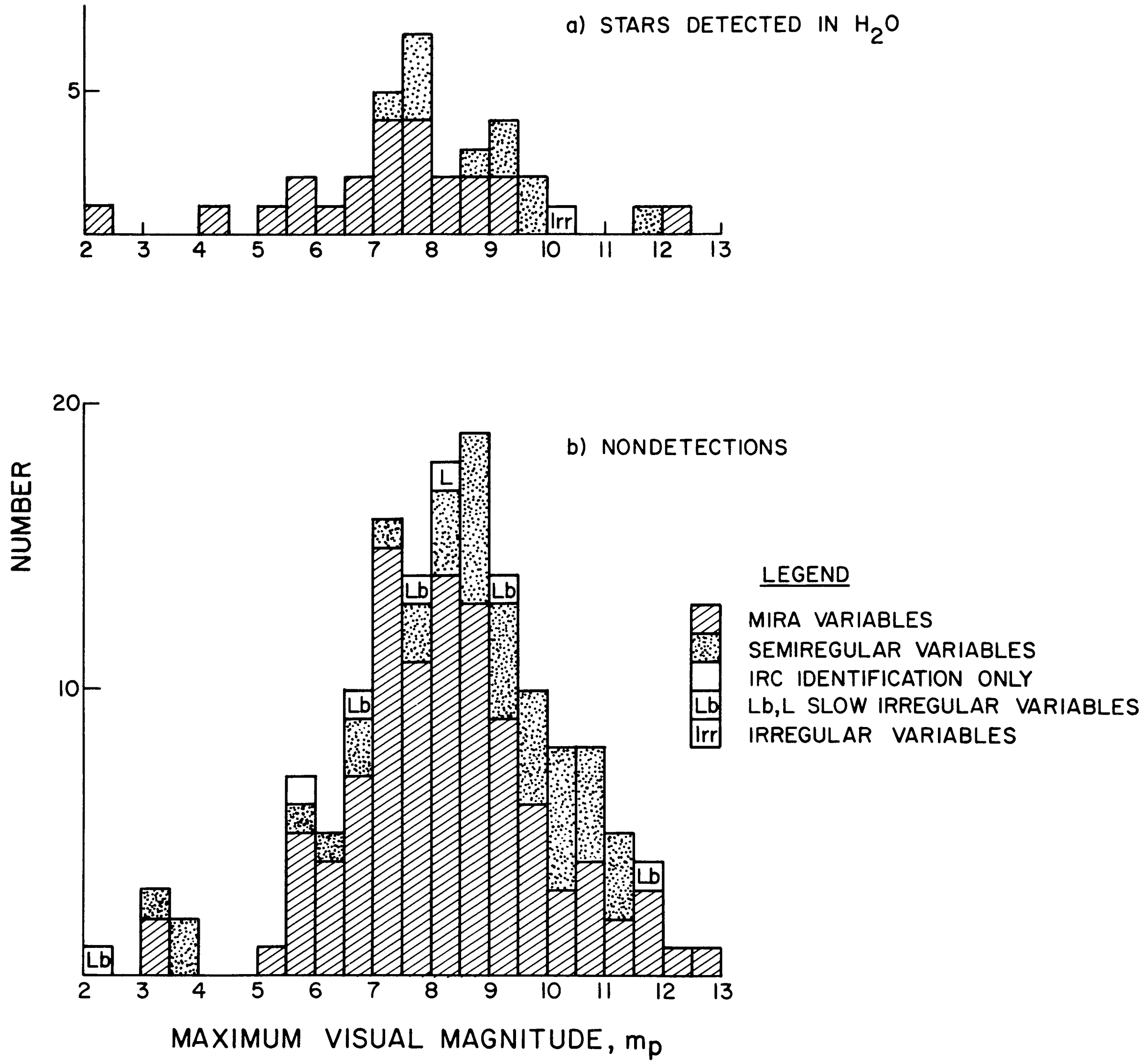

FIG. 24.—Histogram as a function of maximum visual magnitude: (*a*) stars detected in H_2O; (*b*) stars for which H_2O was not found.

change by 2.5 to 8 mag. This extreme change in the H_2O stars probably reflects the fact that their peak flux occurs in the near-infrared, making for a greater relative change at optical wavelengths. The only apparent exception is IK Tau (NML Tau), whose visual change is only 4.6 mag. This, however, is probably incorrect, reflecting only the fact that this star has not yet been observed at minimum light (Wing and Lockwood 1973). The infrared continuum at 1.04 μ has one of the largest changes known for a Mira variable, being greater than 2 mag. Robert F. Wing (1974) suggests that the visual minimum may well be 2 or more mag beyond the value of 16.5 given by Kukarkin. We note another unusual property of this star in Figure 27 (K mag versus maximum visual mag): IK Tau falls among the semiregular variables rather than among the main band of Miras.

4. Figure 27 plots K versus maximum m_p where both these quantities are known. For the Miras, the trend is fairly uniform; i.e., those stars that are brighter in the infrared are brighter in the visual as well. No such trend exists for the semiregular stars, but the plot suggests that for any given value of m_p, the semiregular variables are brighter in the infrared than the Miras. This may be why semiregular variables can be strong OH–H_2O maser sources and yet not show the extreme change in visual magnitude discussed in paragraph (3).

5. Only five of 42 H_2O–infrared stars do not show OH: RX Boo, R Tau, RT Vir, RT Aql, and SV Peg. All but SV Peg have been checked to less than 1 Jy at 1612 MHz. RX Boo and RT Vir have also been checked in the main lines, and R Tau was searched at 1667 MHz. More sensitive searches at light maximum may well reveal OH emission.

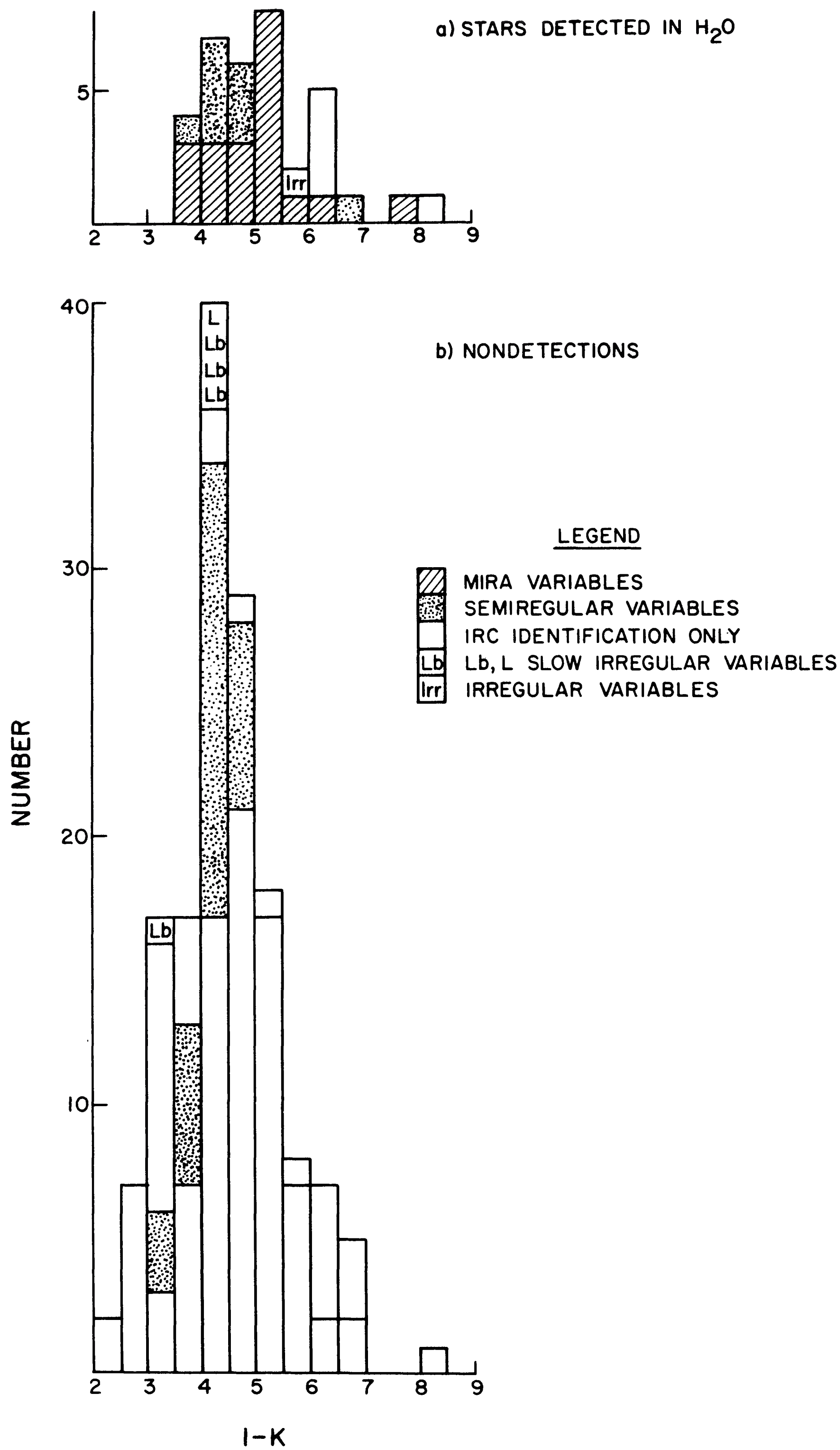

FIG. 25.—Histogram as a function of $I-K$ index: (a) stars detected in H_2O; (b) stars for which H_2O was not found

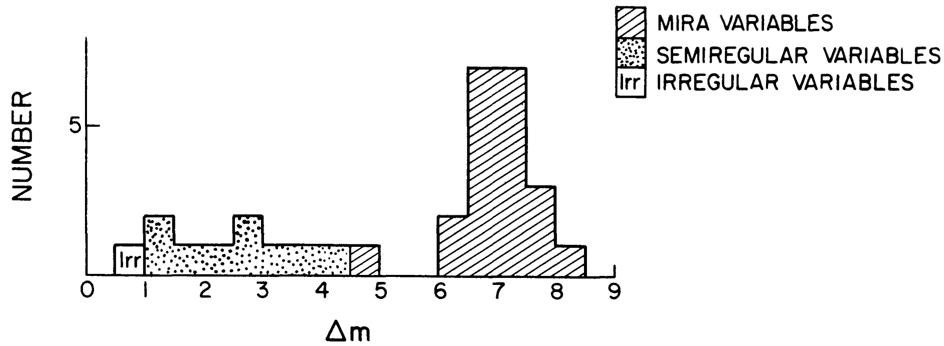

FIG. 26.—Histogram as a function of differential change in visual magnitude for H_2O–infrared stars

6. Maser emission from vibrationally excited SiO is present in many H_2O–infrared stars. Fourteen of 16 stars surveyed by Snyder and Buhl (1975) are also H_2O emitters. Two significant exceptions are R Hya and χ Cyg, both of which are classified as S stars. No S star has ever shown radio-frequency water emission.

7. The H_2O–infrared stars with known optical spectral class are all late M. Two or three supergiants, notably PZ Cas and S Per, are as early as M3, but these are exceptional. This property has been reasonably well established from previous work; this study tended to concentrate on the late M stars.

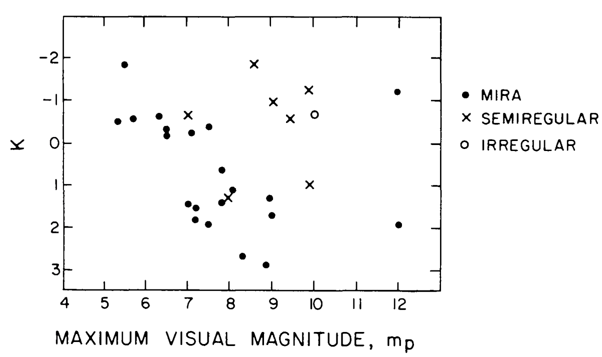

FIG. 27.—Plot of K magnitude versus visual magnitude for H_2O–infrared stars.

8. Eight of the 22 new water stars were examined more than once, and all show changes in intensity with time. Previous work (cf. Schwartz *et al.* 1974; Dickinson *et al.* 1973) revealed time variability as a common feature of many H_2O–infrared stars, and it seems certain that it is common to all. No effort was made to monitor sources on a regular basis, but TW Peg dropped in intensity dramatically near the bottom of its light curve, consistent with the conclusions of Schwartz *et al.* (1974), who noted that the radio flux is in phase with the visual brightness. The same effect was found by Harvey *et al.* (1974) with respect to OH. Similarly, the first clear detection of PZ Cas occurred on the ascendant part of its light curve, after three marginal efforts had been made to detect it during descending light and near minimum.

A number of people have made data available to me before publication. Others have offered critical comments, suggestions, and encouragement. It is a pleasure to thank Drs. Eric Chaisson, George Herbig, Edward Lilley, Marvin Litvak, Louis Pataki, Cecilia Payne-Gaposchkin, Phillip Schwartz, Lewis Snyder, John Spencer, Patrick Thaddeus, Barry Turner, George Wallerstein, Nicholas Woolf, and Sigfrid Yngvesson. I would also like to express my appreciation to Dr. M. L. Meeks and the staff of the Haystack Observatory.

APPENDIX A

NEGATIVE RESULTS by (right ascension)

SS Cas	UZ Per	IRC+40184	R UMi	GY Aql	IRC+40483
LK Hα 198	RT Eri	U Pup	SS Oph	χ Cyg	UU Peg
IRC+80001	SU Eri	R Cnc	IRC+40390	VS 4865	W Cyg
T Cet	IRC+40069	IRC+40201	R Oph	RR Sgr	S Cep
T Cas	V Eri	W Cnc	UY Oph	RS Aql	RU Cyg
T Psc	S 208	RS Cnc	α Her	V1943 Sgr	μ Cep
IRC+80002	IR Per	Y Dra	IRC+00301	IRC−10529	IRC+00509
Y Cep	IRC+30090	IRC−20197	G 353.2+0.9	RU Aql	WY Cyg
IRC+40011	S Tau	R UMa	G 351.6−1.3	RT Sgr	T Peg
TY Cas	T Cam	V Hya	SY Dra	SX Cyg	IRC+10510
BD+61154	R Cae	W Leo	SU Oph	AU Cyg	RS Peg
VY Cas	TX Cam	IRC+40221	V337 Her	CN Cyg	SS Aqr
RV Cas	UV Eri	IRC+40223	IRC−10381	T Mic	RV Peg
KS Cas	IRC−20067	R Com	OH 1750−26	IRC+40422	S Lac
S 186	IRC+50137	BK Vir	IRC+50274	RW Cyg	S 138
IRC+40019	IRC+50139	Y UMa	IRC+40307	IRC+40431	LK Hα 233
VZ Cas	R Aur	SW Vir	V454 Oph	EU Del	RX Lac
S Psc	IRC+40119	R Hya	RT Dra	TX Cap	S Aqr
IRC+80003	IRC+40121	S Vir	IRC−10424	Y Del	S 148
U Per	S Ori	IRC+60226	X Oph	S Del	SZ And
IRC+50049	RU Aur	IRC+40253	IRC−10450	Y Aqr	β Peg
IRC+10025	V 380 Ori	RR Boo	RW Lyr	DG Cyg	R Peg
IRC+40036	U Aur	V Boo	δ Lyr	W Aqr	V Cas
R Ari	V Cam	R Boo	IRC+40329	V Del	MWC 1080
W And	IRC+50156	S Ser	R Lyr	RR Cap	S Peg
R Cet	W Cam	RS Lib	V Lyr	DH Cyg	Z Cas
RR Per	U Lyn	Y CrB	RU Lyr	HD 200775	R Aqr
UX And	S Lyn	ST Her	XY Aql	Y Equ	TX Psc
R Tri	IRC+40162	R Ser	R Sgr	RS Cap	RS And
T Ari	IRC−20105	RR Lib	Z Sgr	IRC+30469	RR Cas
ER Per	SW Gem	RS CrB	T Sge	X Cep	
S 201	AM Gem	R Her	UV Cyg	TW Cyg	
ρ Per	V CMi	DX Ser	BG Cyg	T Cep	
U Ari	S CMi	RU Her	RT Cyg	V Mic	
IRC+40059	T CMi	G Her	X Aql	RW Aqr	

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