1990ApJ...350L..41M

THE ASTROPHYSICAL JOURNAL, 350: L41–L44, 1990 February 20

SUBMILLIMETER WATER MASERS

KARL M. MENTEN AND GARY J. MELNICK
Harvard-Smithsonian Center for Astrophysics

AND

THOMAS G. PHILLIPS
California Institute of Technology
Received 1989 November 16; accepted 1989 December 7

ABSTRACT

We report the first astronomical detection of the $10_{29} \rightarrow 9_{36}$ transition of water vapor (H_2O) at a frequency near 321 GHz. Using the Caltech Submillimeter Observatory we detected the line toward the star-forming regions W3(OH), W49N, W51 IRS 2, and W51 Main, and the supergiant star VY CMa. In all cases, probably, maser action is observed. Since the 10_{29} level of H_2O is at an energy of 1861 K above the ground state, the $10_{29} \rightarrow 9_{36}$ line probes very hot molecular material. The $10_{29} \rightarrow 9_{36}$ emission is found at velocities that are near the systemic velocities of the regions studied. The strongest features in spectra of the well-studied 22 GHz $6_{16} \rightarrow 5_{23}$ transition are generally found at similar velocities. Our $10_{29} \rightarrow 9_{36}$ spectra do not show counterparts to the high-velocity features observed in the 22 GHz line, but this may be due to the limited sensitivity of our observations.

Subject headings: interstellar: molecules — masers — stars: circumstellar shells — stars: formation — stars: late-type

I. INTRODUCTION

Water (H_2O) is thought to be one of the most abundant molecules in interstellar molecular clouds and circumstellar envelopes around late-type stars. Since water is also a constituent of Earth's atmosphere, most of its many transitions in the submillimeter and infrared range are unobservable with ground-based telescopes. Much of the available observational information on extraterrestrial water has thus been obtained from the $6_{16} \rightarrow 5_{23}$ line at 22 GHz, which, because of its high upper level energy of 643 K, can be observed from the ground. The 22 GHz line is always found to show maser emission, often very intense, and therefore represents an important signpost for its exciting sources, which are deeply embedded in the dense molecular cloud cores that are sites of ongoing star formation. Spectral features with velocities that are very high (up to 200 km s^{-1}) relative to the local molecular cloud velocities are frequently observed in this line, giving evidence for outflow motions that are thought to originate from the embedded young (proto-)stellar objects (see Reid and Moran 1988 for a review). Masers at 22 GHz are also found in very many late-type stellar envelopes. The discovery of other water maser transitions may place important constraints on the still unclear excitation mechanism for the 22 GHz masers.

Two relatively low excitation rotational lines at 183 and 380 GHz (Waters *et al.* 1980; Phillips, Kwan, and Huggins 1980), which are most likely masing, have been detected using airborne instrumentation, but only toward the Orion–KL star-forming region. Recently, Menten and Melnick (1989) discovered two rotational transitions from the v_2 vibrationally excited state toward the supergiant star VY CMa. These lines have energies above the ground state in excess of 3000 K, and their detection raises the question whether other high-excitation water lines are observable in wavelength regions accessible from the ground. In this *Letter* we report the first observations of the $10_{29} \rightarrow 9_{36}$ rotational transition within the vibrational ground state of H_2O toward a number of star-forming regions and a late-type star. Since this transition has an upper level energy of $E_u/k = 1861$ K, our measurements probe highly excited molecular material in the observed regions.

II. OBSERVATIONS

The observations were made on 1989 September 26 and 27 using the 10.4 m telescope of the Caltech Submillimeter Observatory on Mauna Kea, Hawaii. A liquid helium–cooled SIS mixer receiver (Ellison *et al.* 1989) was used in double-sideband (DSB) mode with the upper sideband (USB) operating at 321.22564 GHz, the rest frequency of the $10_{29} \rightarrow 9_{36}$ line of H_2O (De Lucia *et al.* 1972). Since in this receiver the lower sideband (LSB) is centered at a 2.8 GHz lower frequency, it was possible to simultaneously observe the $8_1 \rightarrow 8_0 A^{\mp}$ line of methanol (CH_3OH), which has a rest frequency of 318.318793 GHz (Pickett *et al.* 1981). The measurement uncertainties of the quoted rest frequencies are 0.15 MHz (H_2O) and 0.015 MHz (CH_3OH), corresponding to velocity uncertainties of 0.14 and 0.014 km s^{-1} for the H_2O and CH_3OH lines, respectively. DSB receiver temperatures and total system temperatures were typically of order 350 and 2500 K, respectively. The data were taken in position-switching mode and calibrated using the chopper wheel method. The pointing was checked by observations of the planets Saturn and Jupiter and estimated to be accurate within 5″. At 321 GHz the telescope has a half-power beam size of 23″. We present our data in main-beam brightness temperature T_{MB} units, assuming a main-beam efficiency of 0.6. A T_{MB} of 1 K corresponds to a flux density of 44 Jy. Calibration errors introduced by atmospheric fluctuations and the uncertain signal-to-image sideband gain ratio are estimated to be less than 30%. The spectral lines were detected with a 1024 channel acousto-optic spectrometer (AOS) (Masson 1982) with a bandwidth of 500 MHz, resulting in a channel spacing of 0.49 MHz, corresponding to 0.46 km s^{-1}, and an effective velocity resolution of 1.23 MHz (1.15 km s^{-1}).

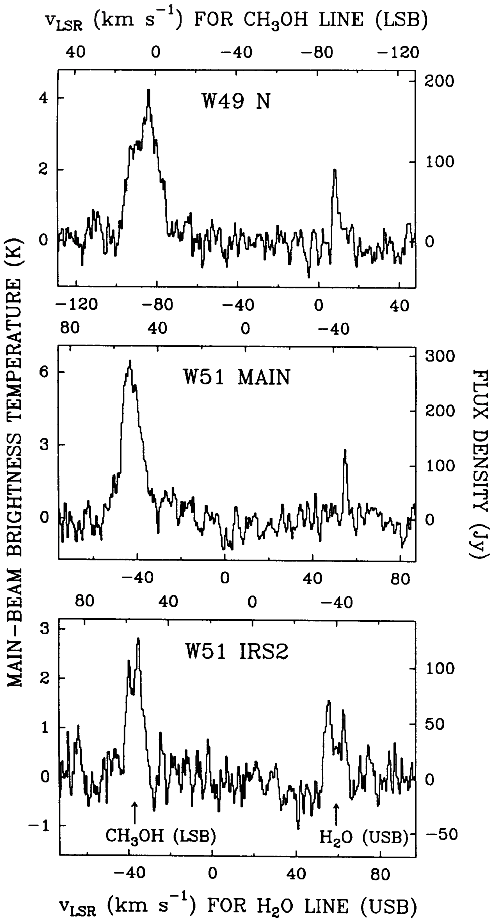

FIG. 1.—Spectra observed toward the 22 GHz water maser positions associated with the star-forming regions W49N (*top*), W51 Main (*middle*), and W51 IRS 2 (*bottom*). The 318 GHz CH_3OH $8_1 \rightarrow 8_0 A^{\mp}$ and the 321 GHz H_2O $10_{29} \rightarrow 9_{36}$ lines appear on the left-hand and right-hand side of each spectrum, respectively. The H_2O line was detected in the upper sideband (USB), and velocities relative to its rest frequency are given by the lower velocity axis of each panel, while the upper velocity axis corresponds to the CH_3OH line, which was measured in the lower sideband (LSB). Intensity scales in T_{MB} and flux density units are given as left and right *y*-axis, respectively. Linear baselines have been subtracted from all spectra.

To compare emission from the $10_{29} \rightarrow 9_{36}$ transition with spectra of the well-studied $6_{16} \rightarrow 5_{23}$ transition of water at a frequency of 22.23508 GHz, we observed the latter line toward some of our target sources using the 36.6 m antenna of Haystack Observatory, near Westford, Mass. The observations were made on 1989 October 21 using a *K* band maser amplifier and a 512 channel autocorrelator spectrometer with a velocity resolution of 0.53 km s^{-1}. The beam size was 90″.

III. RESULTS AND DISCUSSION

a) Detection of the $10_{29} \rightarrow 9_{36}$ Line of Water

We detected emission in the $10_{29} \rightarrow 9_{36}$ transition of water toward the star-forming regions W49N, W51 IRS 2, W51 Main (Fig. 1), and W3(OH) (Fig. 2) and toward the supergiant star VY CMa (Fig. 3). The observational results are summarized in Table 1. All these sources are prominent 22 GHz water maser emitters, with the W49N region being the most luminous 22 GHz source in the Galaxy. The frequency of the $8_1 \rightarrow 8_0 A^{\mp}$ transition of methanol was within the bandpass of the image sideband, and the methanol line shows up prominently in the spectra taken toward the observed star-forming regions (Figs. 1 and 2), while it is not detected toward VY CMa, consistent with the fact that no CH_3OH emission has ever been observed toward a late-type star. By shifting the local oscillator frequency, we verified the assignments of the H_2O and CH_3OH lines to signal and image sideband, respectively. Examination of the comprehensive SLAIM spectral line atlas (Lovas 1984) did not bring forward any other candidate spectral line to challenge the identification of the H_2O transition, which in all cases appears at LSR velocities that are well established as the local velocities of the hot, dense moleular material in the regions in question.

b) Comparison of 321 and 22 GHz Water Emission

Because the observed linewidths of the H_2O $10_{29} \rightarrow 9_{36}$ transition toward W49N, W51 Main, and W3(OH) are much smaller than the methanol linewidths, the H_2O line is probably masing. For example, in W51 Main, the width of the $10_{29} \rightarrow 9_{36}$ line, "deconvolved" from our velocity resolution of

TABLE 1
PARAMETERS DETERMINED FROM H_2O $10_{29} \rightarrow 9_{36}$ OBSERVATIONS

Source (1)	α_{1950} (2)	δ_{1950} (3)	D (kpc) (4)	$\int T_{MB}\,dv$ (K km s^{-1}) (5)	v_{LSR}[a] (km s^{-1}) (6)	Δv[a] (km s^{-1}) (7)	L[b] (s^{-1}) (8)	L_{22}/L_{321}[c] (9)
W3(OH)	02^{h}23^{m}17^s.3	61°38′58″	2.2	6.6(0.4)	−47.8(0.1)	2.4(0.2)	8.6×10^{44}	70
W49N	19 07 49.8	09 01 17	10.5	9.9(0.8)	[6, 18][d]	...	2.9×10^{46}	150
W51 IRS 2	19 21 22.3	14 25 15	7.0	12.8(1.2)	[53, 66][e]	...	1.7×10^{46}	5[f]
W51 Main	19 21 26.2	14 24 43	7.0	4.3(0.4)	54.8(0.1)	1.5(0.2)	5.7×10^{45}	39
VY CMa	07 20 54.7	−25 40 12	1.5	19.5(0.4)	[11, 25]	...	1.2×10^{45}	12

[a] In the case of W3(OH) and W51 Main, LSR velocity and line width (FWHP) as determined from Gaussian fits are listed. The velocity resolution was 1.15 km s^{-1}. For the other sources, the total velocity range showing $10_{29} \rightarrow 9_{36}$ emission (FWZP) is given.
[b] The isotropic photon luminosities L were calculated assuming the distances listed in col. (4).
[c] Ratio of isotropic photon luminosities observed in the 22 GHz $6_{16} \rightarrow 5_{23}$ and 321 GHz $10_{29} \rightarrow 9_{36}$ transitions integrated over the velocity range over which $10_{29} \rightarrow 9_{36}$ emission is observed. In the case of VY CMa, the 22 GHz data were measured on 1989 January 31 by Menten and Melnick 1989. All other observations were made on the dates given in the text.
[d] A narrow ($\Delta v = 2.3$ km s^{-1}) feature is observed at an LSR velocity of 8.2 km s^{-1}.
[e] Two narrow features are observed at velocities of 55.5 and 62.7 km s^{-1}, respectively.
[f] A correction of the W51 IRS 22 GHz flux density for the effects of the very strong emission from nearby W51 Main picked up within our large (90″) beam at 22 GHz results in a lower luminosity ratio of $L_{22}/L_{321} \approx 3$.

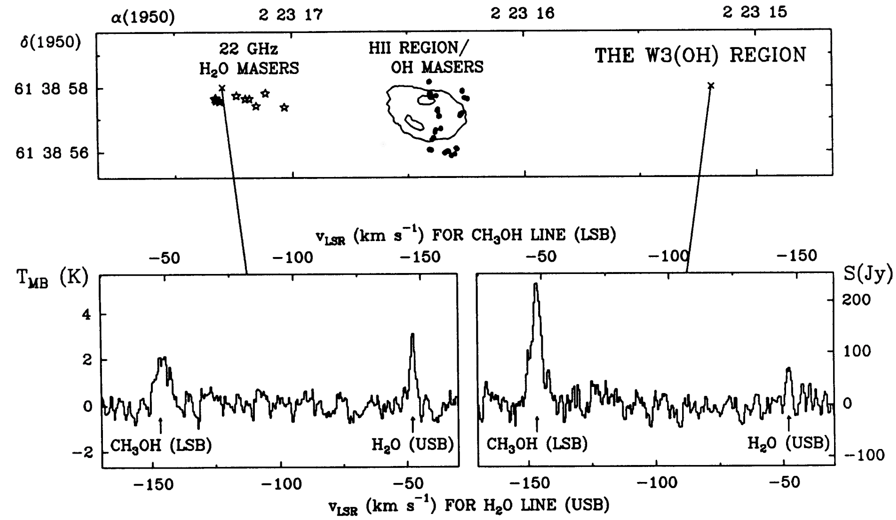

FIG. 2.—An overview of the W3(OH) star-forming region is given in the upper part of the figure: The 1665 OH masers mapped by Reid *et al.* (1980) (*black dots*) are found in the immediate neighborhood of the ultracompact H II region which is indicated by the 10% and 70% contours of the 23.7 GHz VLA continuum map of Guilloteau *et al.* (1983). In contrast, the 22 GHz H_2O masers, denoted by stars, are found east of the H II region (Genzel *et al.* 1978). Our spectra are shown in the lower part of the figure. The (*left*) spectrum was taken, as indicated, toward a position close to the 22 GHz masers, while the spectrum on the right-hand side was taken toward an offset position located 15″ to the west. For each spectrum, the lower velocity axis gives velocities relative to the rest frequency of the H_2O $10_{29} \rightarrow 9_{36}$ line, which appears in the right-hand portion of each spectrum, while the upper velocity axis indicates velocities for the CH_3OH $8_1 \rightarrow 8_0 A^{\mp}$ transition, appearing on the left-hand side of each spectrum. Intensity scales in T_{MB} and flux density units are given on the left and right y-axis, respectively.

1.15 km s^{-1}, is 0.96 km s^{-1}, considerably smaller than the width of the methanol line, which, at 10 km s^{-1}, has the same width as other thermal CH_3OH lines measured toward this source (Menten *et al.* 1986). Narrow water features are also observed in the W51 IRS 2 spectrum, which appears to be more complex than the spectra observed toward the other star-forming regions.

While the 22 GHz spectra of the observed sources show a very large number of high-velocity features covering a total velocity range of up to several hundred km s^{-1}, the $10_{29} \rightarrow 9_{36}$ emission is evident only near the systemic velocities of the observed cloud cores, which are well known from other molecular line data (Fig. 4). However, given the limited sensitivity of our data we would not expect to detect any high-velocity 321 GHz emission if the intensity ratio of even the strongest high-velocity features to the low-velocity emission (i.e., emission near the systemic velocity) in the $10_{29} \rightarrow 9_{36}$ line were equal to that observed in the $6_{16} \rightarrow 5_{23}$ transition. The luminosity of the 22 GHz line integrated over the velocity range showing 321 GHz emission is typically between one and two orders of magnitude greater than that of the 321 GHz line, assuming that both lines are equally beamed.

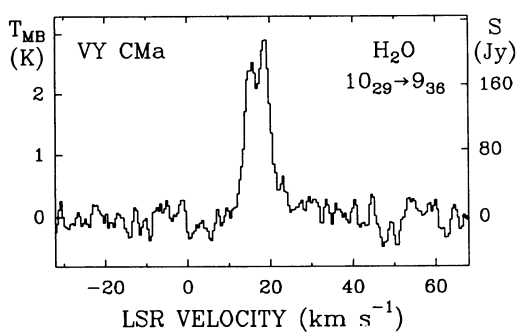

FIG. 3.—Spectrum of the $10_{29} \rightarrow 9_{36}$ line of H_2O observed toward the supergiant star VY CMa. Intensity scales in T_{MB} and flux density units are given on the left and right y-axis, respectively.

Limited observing time precluded studying the spatial distribution of the H_2O emission for all the detected sources. In the case of W49N, a five-point map was measured at $\pm 10''$ offsets in right ascension and declination relative to the position given in Table 1 (which is the position of the dominant 22 GHz maser center), and the water emission distribution was found to be consistent with that of a point source at the 22 GHz position.

Toward W3(OH), a five-point map at $\pm 15''$ (i.e., 65% of the beam size) offsets in right ascension and declination was measured, centered on the position of the 22 GHz H_2O masers, about 6″ east of the compact H II region. In Figure 2 we give an overview of the W3(OH) region and show the spectra taken at offsets (0, 0) and ($-15''$, 0): while the H_2O $10_{29} \rightarrow 9_{36}$ is stronger than the methanol line at the 22 GHz position, the opposite is true at the offset position. Numerous methanol transitions in the centimeter range have been detected in absorption against the continuum emission of the H II region or showing maser emission arising from the same region as the OH masers (Menten *et al.* 1986, 1988). Since our observations clearly show that the 321 GHz water emission is centered west of the methanol emission, we conclude that it most probably arises from the same region as the 22 GHz water masers, which in turn are associated with a hot dense molecular core $\approx 6''$ east of the H II region (Turner and Welch 1984; Mauersberger, Wilson, and Walmsley 1986).

c) *Hot Water in Star-forming Regions*

Evidence for hot, dense molecular gas has been found previously in high-mass star-forming regions by observations of high-excitation lines of ammonia, methanol, and other molecules, some of them showing maser action. For example, toward W51 IRS 2, maser emission in the NH_3 (11, 9) inversion transition (E_u/k = 1447 K) (Wilson and Henkel 1988) and a

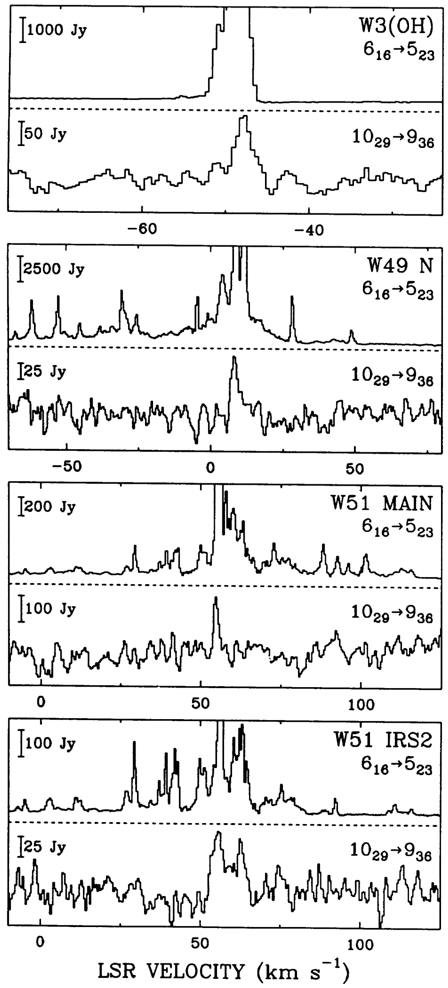

FIG. 4.—A comparison of spectra taken in the 22 GHz $6_{16} \rightarrow 5_{23}$ and 321 GHz $10_{29} \rightarrow 9_{36}$ transitions toward the star-forming regions W3(OH), W49N, W51 Main, and W51 IRS 2 (*top to bottom*). In each panel the 22 GHz line is shown in the upper half. The flux density scale is indicated on the left-hand side of each spectrum. Except in the case of W3(OH), 22 GHz emission is observed over a wider velocity range than shown in the figure, namely over the velocity intervals [−260, 265], [−50, 140], and [−30, 125] km s^{-1} for W49N, W51 Main, and W51 IRS 2, respectively. Also, for display reasons, the strongest emission features have been clipped for all 22 GHz spectra. The peak flux densities are 7100, 16,000, 4500, and 660 Jy for W3(OH), W49N, W51 Main, and W51 IRS 2, respectively. Note that the beamwidth of the 22 GHz observations (90″) is bigger than the separation between W51 Main and IRS 2 (67″), causing strong features in either source to appear in both spectra.

$v = 2$ SiO maser ($E_u/k = 3523$ K) have been reported (Hasegawa *et al.* 1985). The detection of *water* emission from these regions is particularly interesting since H_2O, given its presumed high abundance and the large number of available transitions in the far-infrared range, is of paramount importance for their thermal balance (e.g., Neufeld and Melnick 1987). Observations of the $10_{29} \rightarrow 9_{36}$ line with higher spatial and spectral resolution will certainly give interesting information about the excitation of the 22 GHz H_2O masers. Any viable pumping scheme has to predict maser emission in both lines. In this context, it is interesting to note that recent radiative transfer calculations by Neufeld and Melnick (1990) predict both the $10_{29} \rightarrow 9_{36}$ and the $6_{16} \rightarrow 5_{23}$ lines to be inverted over a wide range of physical conditions.

Most importantly, spectra with an improved signal-to-noise ratio are needed to check on the possible existence of high-velocity $10_{29} \rightarrow 9_{36}$ emission.

d) VY Canis Majoris

The centroid velocity of the $10_{29} \rightarrow 9_{36}$ line toward VY CMa is 18.4 km s^{-1}, identical to the value found for the $6_{16} \rightarrow 5_{23}$ transition by Menten and Melnick (1989) and close to the value of 17.6 ± 1.5 km s^{-1} that Reid and Dickinson (1976) derived for the stellar velocity. Unfortunately, we were not able to obtain a $6_{16} \rightarrow 5_{23}$ spectrum at the time of our 321 GHz observations. Comparing our $10_{29} \rightarrow 9_{36}$ spectrum with the 22 GHz spectrum taken by Menten and Melnick in 1989 January we note that, given our sensitivity, we would not expect to see any of the high-velocity features present in the 22 GHz spectrum if the intensity ratio between high- and low-velocity emission were the same for both lines, which show their strongest emission between velocities of 14 and 20 km s^{-1}. Interestingly, no particularly strong emission feature is present in either line at $v_{LSR} = 22$ km s^{-1}, where both vibrationally excited water lines detected by Menten and Melnick and also several SiO transitions have their strongest component. These differences may reflect the different excitation requirements of the various lines.

We thank the CSO staff for their support during the observations and J. Moran and M. Reid for useful comments on the manuscript. Work at the Caltech Submillimeter Observatory is supported by National Science Foundation grant AST 88-15132.

REFERENCES

De Lucia, F. C., Helminger, P., Cook, R. L., and Gordy, W. 1972, *Phys. Rev. A*, **5**, 487.
Ellison, B. N., Schaffer, P. L., Schaal, W., Vail, D., and Miller, R. E. 1989, *International J. Infrared Millimeter Waves*, **10**, 937.
Genzel, R., *et al.* 1978, *Astr. Ap.*, **6**, 13.
Guilloteau, S., Stier, M. T., and Downes, D. 1983, *Astr. Ap.*, **126**, 10.
Hasegawa, T., *et al.* 1985, in *Masers, Molecules, and Mass Outflows in Star Forming Regions*, ed. A. D. Haschick (Westford, Mass: Haystack Observatory), p. 275.
Lovas, F. J. 1984, SLAIM Magnetic Tape Version I-84, private communication.
Masson, C. R. 1982, *Astr. Ap.*, **114**, 270.
Mauersberger, R., Wilson, T. L., and Walmsley, C. M. 1987, *Astr. Ap.*, **166**, L26.
Menten, K. M., and Melnick, G. J. 1989, *Ap. J.* (*Letters*), **341**, L91.
Menten, K. M., Reid, M. J., Moran, J. M., Johnston, K. J., Wilson, T. L., and Batrla, W. 1988, *Ap. J.* (*Letters*), **333**, L83.
Menten, K. M., Walmsley, C. M., Henkel, C., and Wilson, T. L. 1986, *Astr. Ap.*, **157**, 318.
Neufeld, D. A., and Melnick, G. J. 1987, *Ap. J.*, **322**, 266.
———. 1990, *Ap. J.* (*Letters*), submitted.
Phillips, T. G., Kwan, J., and Huggins, P. J. 1980, in *IAU Symposium 80, Interstellar Molecules*, ed. B. H. Andrew (Dordrecht: Reidel), p. 21.
Pickett, H. M., Cohen, E. A., Brinza, D. E., and Schaefer, M. M. 1981, *J. Molec. Spectrosc.*, **89**, 542.
Reid, M. J., and Dickinson, D. F. 1976, *Ap. J.*, **209**, 505.
Reid, M. J., Haschick, A. D., Burke, B. F., Moran, J. M., Johnston, K. J., and Swenson, G. W., Jr. 1980, *Ap. J.*, **239**, 89.
Reid, M. J., and Moran, J. M. 1988, in *Galactic and Extragalactic Radio Astronomy*, ed. G. L. Verschuur and K. I. Kellermann (New York: Springer), p. 255.
Turner, J. L., and Welch, W. J. 1984, *Ap. J.* (*Letters*), **287**, L81.
Waters, J. W., *et al.* 1980, *Ap. J.*, **235**, 57.
Wilson, T. L., and Henkel, C. 1988, *Astr. Ap.*, **206**, L26.

GARY J. MELNICK and KARL M. MENTEN: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

THOMAS G. PHILLIPS: 320-47 California Institute of Technology, Pasadena, CA 91125