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A NEW SUBMILLIMETER WATER MASER TRANSITION AT 325 GHz

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ABSTRACT

We report the first detection of the $5_{15} \rightarrow 4_{22}$ transition of interstellar water vapor (H_2O) near 325 GHz. Using the Caltech Submillimeter Observatory, we detected this line toward the Orion-KL, W49N, W51 Main, and IRAS 1629A star-forming regions. In all cases, maser action is most likely observed. All of the sources with detected 325 GHz emission are also strongly emitting in the well-studied 22 GHz water maser line. Both lines cover similar velocity ranges and, in particular, toward W49N *both* show high-velocity emission. While the Orion-KL, W49N, and W51 Main maser centers are associated with very luminous infrared and radio continuum sources, IRAS 1629A is a low-luminosity cold *IRAS* source. It is therefore clear that 325 GHz masers can arise in the same variety of sources as the 22 GHz masers. Unfortunately, absorption by terrestrial water vapor currently permits detection of only the very strongest sources. Our instrumental setup allowed simultaneous observations of the $H_2^{18}O$ isotopic equivalent of the $5_{15} \rightarrow 4_{22}$ transition near 322 GHz in the image sideband of the receiver. Toward Orion-KL, we tentatively detected emission at the frequency of the $H_2^{18}O$ line.

Subject headings: interstellar: molecules — masers — stars: formation

I. INTRODUCTION

Maser emission from interstellar water vapor (H_2O) was first detected in the $6_{16} \rightarrow 5_{23}$ transition near 22 GHz (Cheung *et al.* 1969) more than 20 years ago. Since then, the 22 GHz line has been observed toward many hundreds of molecular clouds and late-type stars and turned out to be a useful probe of ongoing star formation in dense cloud core regions (see, e.g., Reid and Moran 1988). Although many models have been developed to explain the excitation of the 22 GHz water masers, attempts to derive meaningful constraints on the physical parameters of the maser sources from observations of a single spectral line have proven difficult. The detections of the $3_{13} \rightarrow 2_{20}$ and $4_{14} \rightarrow 3_{21}$ transitions near 183 and 380 GHz, respectively, using the Kuiper Airborne Observatory did little to relieve this situation, since only a single source, Orion-KL, was detected (Waters *et al.* 1980; Phillips, Kwan, and Huggins 1980), and the maser nature of this emission was not established. The status of water maser observations changed markedly in 1989 when Menten, Melnick, and Phillips (1990) discovered maser emission in the $10_{29} \rightarrow 9_{36}$ transition near 321 GHz toward a number of star-forming regions and a late-type star. Shortly thereafter, Cernicharo *et al.* (1990) established the presence of strong maser action in the 183 GHz line in both interstellar and circumstellar sources. Theoretical calculations by Neufeld and Melnick (1990) subsequently showed that maser emission in the 22 and 321 GHz lines may be expected to occur simultaneously under a wide range of physical conditions, due to the combined effects of collisional excitation and radiative trapping in infrared transitions. Furthermore, Neufeld and Melnick (1991, hereafter NM) predicted that 183 GHz maser emission must almost inevitably be accompanied by maser action in the $5_{15} \rightarrow 4_{22}$ transition near 325 GHz, which had previously been identified as a possible maser line by Oka (1973), Deguchi (1977), and Chandra, Kegel, and Varshalovich (1985). Motivated by this prediction, we have searched for the 325 GHz $5_{15} \rightarrow 4_{22}$ line using the Caltech Submillimeter Observatory, and in this *Letter* we report its first astronomical detection.

II. OBSERVATIONS

The observations were made on 1990 March 22 and April 13 using the 10.4 m telescope of the Caltech Submillimeter Observatory (CSO) on Mauna Kea, Hawaii. A liquid helium–cooled SIS mixer receiver was used in double-sideband (DSB) mode with the upper sideband (USB) operating at 325.152919 GHz, the rest frequency of the H_2O $5_{15} \rightarrow 4_{22}$ line. Since in this receiver the lower sideband (LSB) is centered at a 2.8 GHz lower frequency, it was possible to observe simultaneously the $H_2^{18}O$ $5_{15} \rightarrow 4_{22}$ line, which has a rest frequency of 322.46517 GHz. The measurement uncertainties of the quoted rest frequencies are 0.027 MHz (H_2O) and 0.05 MHz ($H_2^{18}O$) (De Lucia, Helminger, and Kirchhoff 1974), corresponding to velocity uncertainties of 0.025 and 0.047 km s^{-1} for the H_2O and $H_2^{18}O$ lines, respectively. The data were taken in position-switching mode and initially calibrated using the chopper wheel method. However, the (DSB) chopper wheel calibration method intrinsically assumes equal atmospheric opacities τ in both sidebands, whereas in our case $\tau(\text{USB}) \gg \tau(\text{LSB})$; thus the resulting antenna temperatures were further corrected for effects of the different atmospheric attenuation in the USB and the LSB by means of a two-step process. First, 5 minute read-outs of the NRAO radiometer installed at the CSO provided a

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series of measurements of the atmospheric opacity at 225 GHz over the course of our observations. Second, using both the available site data, summarized by Masson (1990), and model atmospheric calculations, a relationship was found between τ(225 GHz) and the zenith precipitable water vapor (PWV). With the resulting PWV values and the known telescope elevation angle, the atmospheric model was then used to calculate the attenuation in each sideband. The resulting corrected 325 GHz antenna temperatures were converted into Jy by assuming an aperture efficiency of 0.45. Overall, we estimate our absolute calibration to be accurate to within $\approx 40\%$. The pointing was checked by observations of Jupiter and found to be accurate to $\approx 10''$. To minimize calibration errors due to pointing uncertainties, whenever we detected a signal toward any source, we (1) performed a five-point raster around the starting position with half-beam (11″) spacing in azimuth and elevation, (2) determined the peak position of the emission, and (3) obtained a longer integration on this peak position. Because of the limited observing time, no five-point raster could be carried out in the case of Orion-KL. The spectral lines were detected simultaneously using two 1024 channel acousto-optic spectrometers (AOS) with bandwidths of 50 and 500 MHz, channel spacings of 0.049 and 0.49 MHz, and effective velocity resolutions of 0.11 and 1.1 km s^{-1}.

III. RESULTS AND DISCUSSION

a) First Detection of the 325 GHz $5_{15} \rightarrow 4_{22}$ *Line of* H_2O

We initially detected emission in the 325 GHz $5_{15} \rightarrow 4_{22}$ transition of H_2O during our first observing session on 1990 March 22 toward the well-studied Orion-KL and W49N star-forming regions, as well as toward the cool *IRAS* source IRAS 16293−2422 (hereafter IRAS 1629A), a low-mass molecular core in the Ophiuchus molecular cloud system. For the latter two sources, we were able to obtain improved spectra during our second observing run on 1990 April 13, during which we also detected the 325 GHz line toward W51 Main. Spectra of all detected sources are shown in Figures 1–3, and the observed line parameters are listed in Table 1. For IRAS 1629A we compare our 325 GHz spectrum with a spectrum of the 22 GHz $6_{16} \rightarrow 5_{23}$ transition taken at the Haystack Observatory approximately 2 months earlier (Fig. 2). It is clear, in particular from the Orion-KL spectrum, that line emission from the image (lower) sideband (LSB), can potentially contaminate emission in the signal (upper) sideband (USB). Because our signal sideband is centered within an atmospheric absorption feature, the LSB emission experiences much less atmospheric attenuation than the USB emission, making image sideband contributions particularly hazardous. To verify the identification of the 325 GHz H_2O line, we took a few spectra after shifting the local oscillator frequency. This procedure causes the velocities of LSB and USB emission features to shift in opposite directions and clearly established the identification of the H_2O line. No strong molecular emission was found to be present in the LSB that could possibly contaminate the velocity range covered by the H_2O emission. We also checked the comprehensive SLAIM molecular line atlas (Lovas 1984) and found no spectral line in either LSB or USB at the frequencies in question that would be detectable at our sensitivity level.

Two arguments suggest that the observed spectra are the result of maser action and not thermal emission. First, all sources except Orion-KL show emission features with linewidths (<1 km s^{-1}) that are much smaller than those of

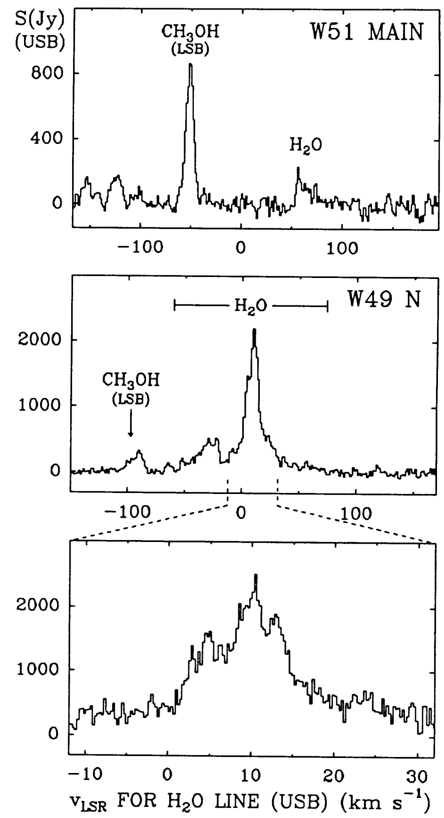

FIG. 1.—Spectra observed toward the star-forming regions W51 Main and W49N. The velocity scale is appropriate for the 325 GHz $5_{15} \rightarrow 4_{22}$ transition of H_2O, which was measured in the upper sideband (USB) of the SIS receiver. In addition to the water line, toward both sources emission from the 322 GHz $9_1 \rightarrow 9_0\,A^{\mp}$ transition of CH_3OH is clearly detected in the lower sideband (LSB). The intensity scale is appropriate only for the USB emission. The W51 Main (*top panel*) and W49N (*middle panel*) spectra both have velocity resolutions of 1.35 km s^{-1}. Toward W49N, water maser emission is observed, as indicated, over a wide velocity range, a portion of which is covered by the high-resolution (0.27 km s^{-1}) spectrum shown in the bottom panel.

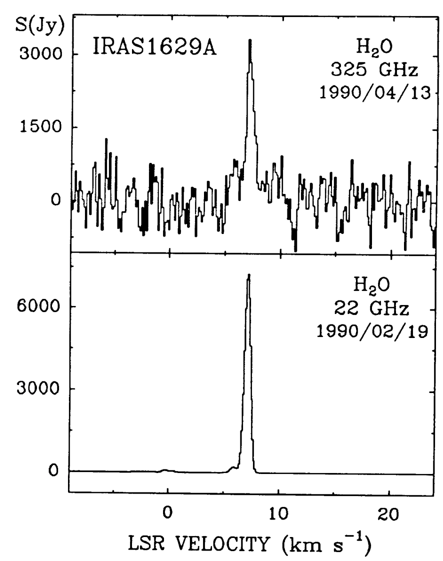

FIG. 2.—Spectra of the 325 GHz $5_{15} \rightarrow 4_{22}$ (*top*) and the 22 GHz $6_{16} \rightarrow 5_{23}$ (*bottom*) transitions of H_2O detected toward the *IRAS* source IRAS 16293−2422. The spectra were observed on different dates as indicated in the figure. The velocity resolutions of the spectra are 0.135 and 0.110 km s^{-1} for the 325 and 22 GHz spectra, respectively.

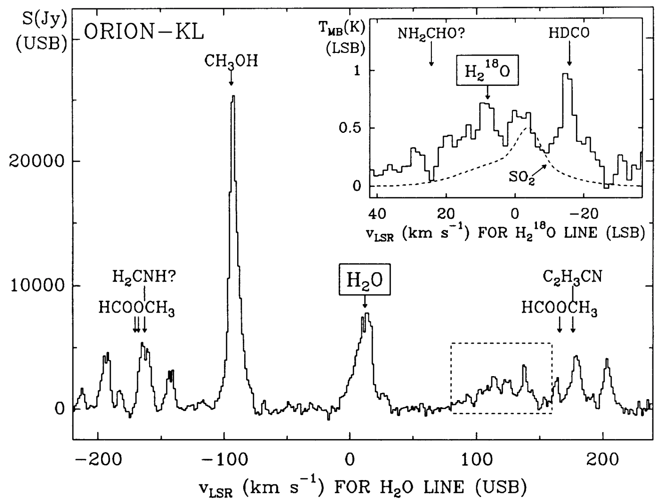

FIG. 3.—Spectrum observed toward the Orion-KL star-forming region. The 325 GHz $5_{15} \rightarrow 4_{22}$ line of H_2O, measured in the upper sideband (USB), appears at the center of the spectrum. All other lines are detected in the lower sideband (LSB). Velocities at which some of these LSB lines are expected to appear are indicated together with the name of the molecular species. Several relatively strong features cannot presently be identified. The intensity scale (in Jy) is appropriate only for USB emission and the velocity scale is relative to the rest frequency of the H_2O $5_{15} \rightarrow 4_{22}$ line.

In contrast, the velocity scale of the inset, showing, as indicated, a blow-up of the portion of the spectrum enclosed in the dashed box, is relative to the rest frequency of the 322.4 GHz $H_2^{18}O$ isotopic counterpart of the $5_{15} \rightarrow 4_{22}$ line, which was within the LSB frequency range. The spectral feature possibly representing $H_2^{18}O$ emission (assuming $v_{LSR} = 8$ km s^{-1}) is indicated. The arrows mark the velocities at which emission from NH_2CHO and HDCO would be expected to appear. The dashed curve outlines the shape expected for the $34_{4,30} \rightarrow 33_{5,29}$ transition of SO_2. The intensity scale of the inset is in units of main-beam brightness temperature (T_{MB}). A T_{MB} of 1 K corresponds to a flux density of 44 Jy.

known thermal emission lines from other molecules observed toward the same regions. Second, the *total* velocity range covered by 325 GHz line emission in W49N is much larger than the velocity range of thermal molecular emission in this source. Other water maser transitions also show high-velocity emission toward W49N (see next section).

i) *W49N*

W49N is the most luminous 22 GHz maser source in the Galaxy (see, e.g., Walker, Matsakis, and Garcia-Barreto 1982). In the 325 GHz line, W49N also is by far the most luminous of the sources we detected (see Table 1). Both blue- and redshifted high-velocity emission is clearly observed up to 70 km s^{-1} from the systemic velocity. Our spectrum (Fig. 1) bears a striking resemblance to the spectrum of the 183 GHz $3_{13} \rightarrow 2_{20}$ line presented by Cernicharo *et al.* (1990). Both the 183 GHz and the 22 GHz lines show emission over a total velocity range of 400–500 km s^{-1}, but the very high velocity emission is typically much weaker than the low-velocity emission, defined here as emission within ± 50 km s^{-1} of the systemic velocity. Given our limited sensitivity, we would not expect to detect this very high velocity emission in the 325 GHz line if the ratio of high-velocity to low-velocity emission is the same as for the 183 and 22 GHz emission. The 321 GHz $10_{29} \rightarrow 9_{36}$ transition clearly shows a smaller velocity range than all the other water lines (Menten, Melnick, and Phillips 1990). This result may reflect the fact that (except at very high temperatures) the 321 GHz transition shows the least negative opacity of any of the mentioned H_2O maser transitions (see NM) and can therefore reach saturation only in the most highly elongated structures. If H_2O maser emission arises from shells compressed by outflows, then the longest gain path will occur perpendicular to the outflow direction—thus accounting for the fact that no 321 GHz masers are observed at velocities greatly different from the systemic velocity.

ii) *W51 Main*

The 325 GHz spectrum taken toward W51 Main (Fig. 1) has a relatively low signal-to-noise ratio. Menten, Melnick, and Phillips (1990) measured the 22 and 321 GHz H_2O lines toward this source, and it is clear that the 325 GHz line covers the same velocity interval as the strongest 22 GHz emission. The 22 GHz line shows high-velocity emission covering a total range of 190 km s^{-1}. As in the case of W49N, we would not expect to detect this high-velocity emission in the 325 GHz line if both the 325 and 22 GHz lines had a similar intensity ratio of high-velocity to low-velocity emission. As in W49N, the 321 GHz emission in W51 Main covers a much smaller velocity range than either the 22 or 325 GHz lines.

iii) *IRAS 1629A*

The detection of the 325 GHz H_2O transition toward IRAS 1629A is particularly interesting since it clearly proves that this line, like the 22 and 183 GHz transitions, can arise in a wide variety of sources. In contrast to the other detected sources, IRAS 1629A has a very low bolometric luminosity of only 27 $L_\odot$. It is embedded in a dense molecular core (Walker *et al.* 1986; Menten *et al.* 1987) and shows weak compact radio continuum emission, indicating that is the site of recent star formation (Wootten 1989). A strong 22 GHz H_2O maser, first discovered by Wilking and Claussen (1987), was mapped using the VLA by Wootten (1989).

TABLE 1

PARAMETERS DETERMINED FROM OBSERVATIONS OF THE H_2O $5_{15} \rightarrow 4_{22}$ LINE AT 325 GHz

Source (1)	α_{1950} (2)	δ_{1950} (3)	D (kpc) (4)	$\int S\,dv$ (Jy km s^{-1}) (5)	v_{LSR} (km s^{-1}) (6)	Δv[a] (km s^{-1}) (7)	L[b] (s^{-1}) (8)
Orion-KL	$05^h32^m46^s.8$	−05°24′25″	0.45	130,000 (3000)	[−8.2, 32.2]	...	1.6×10^{46}
IRAS 1629A	16 29 21.0	−24 22 16	0.16	2600 (200)	7.16 (0.03)	0.83 (0.09)	4.1×10^{43}
W49N	19 07 49.8	09 01 17	10.5	52,000 (700)	[−60, 74]	...	3.5×10^{48}
W51 Main	19 21 26.2	14 24 43	7.0	2300 (300)	[53, 75]	...	6.7×10^{46}

[a] In the case of IRAS 1629A, LSR velocity and line width (FWHP) as determined from a Gaussian fit are listed. The channel spacing in the fitted spectrum was 0.14 km s^{-1}. For the other sources, the total velocity range showing $5_{15} \rightarrow 4_{22}$ emission (FWZP) is given.

[b] The isotropic photon luminosities L are calculated assuming the distances listed in col. (4).

As is evident from Figure 2, the 22 and 325 GHz water maser spectra are nearly identical: both show a strong, narrow feature at an LSR velocity of 7.1 km s^{-1}, about 3 km s^{-1} higher than the velocity of thermal emission from other molecules. In the 22 GHz line, several other spectral components are found between velocities of -6.1 and 9.8 km s^{-1}, the strongest of which is ≈ 20 times weaker than the 7.1 km s^{-1} feature. Although the 22 GHz maser emission from IRAS 1629A is strongly variable on time scales of several months, all available spectra taken since its first discovery in 1986 April show intense emission at 7.1 km s^{-1}.

iv) *Orion-KL*

Toward Orion-KL, we find strong H_2O $5_{15} \rightarrow 4_{22}$ emission over the velocity range covered by the so-called low-velocity 22 GHz masers (Genzel *et al.* 1981). Although no very narrow features are discernible in our spectrum (Fig. 3), the 325 GHz line is most certainly inverted. To what extent the emission is due to maser action is not known at this time.

In the 183 GHz line, Cernicharo *et al.* (1990) observed a broad emission pedestal, on top of which several narrow features are superposed. Comparison of our spectrum with their 183 GHz spectra is not straightforward, given the difference in beam sizes (22″ vs. 14″) and our pointing uncertainties. Cernicharo *et al.* mapped the KL region with a 10″ spacing and found the overall morphology of the 183 GHz maser distribution to be similar to that of the 22 GHz masers. Mapping of the 325 GHz emission, which we were unable to perform, would be highly desirable to allow a comparison of all the different H_2O masers. We note that in Orion-KL, high-velocity masers present in the 22 GHz spectra, i.e., components with velocities outside the [-10, 30] km s^{-1} velocity interval (Genzel *et al.* 1981), are typically much weaker than the low-velocity emission. Weak 325 GHz high-velocity components would be difficult to detect in our spectrum, given the low signal-to-noise ratio and the line contamination from the image sideband.

b) *Tentative Detection of the* 322 GHz $5_{15} \rightarrow 4_{22}$ *Line from the* $H_2^{18}O$ *Isotope*

As shown in Figure 3, our Orion-KL spectrum has a spectral feature at the frequency of the 322 GHz $5_{15} \rightarrow 4_{22}$ transition of $H_2^{18}O$ in the LSB. If real, this detection is of great interest since comparison with the recent tentative detection of the 203 GHz $3_{13} \rightarrow 2_{20}$ line of $H_2^{18}O$ (Jacq *et al.* 1988) would, in principle, allow an estimate of the water rotation temperature and column density in Orion-KL to be derived. Unfortunately, due to contamination by other lines, an analysis of the possible $H_2^{18}O$ features detected by us and by Jacq *et al.* is not straightforward. In particular, to determine the parameters of the 322 GHz line, the line shape of the adjacent high-excitation SO_2 $34_{4,30} \rightarrow 33_{5,29}$ transition must be modeled. We defer all quantitative analysis to a future paper. In Figure 3 (*inset*) the dashed line represents a (preliminary) prediction for the shape and intensity of the SO_2 line, which at the velocity of the $H_2^{18}O$ line contributes only broad line wing emission. Therefore, the rather narrow ($\Delta v \approx 4$ km s^{-1}) feature that we tentatively identify as the $H_2^{18}O$ $5_{15} \rightarrow 4_{22}$ line cannot be accounted for as SO_2 emission.

c) *Interpretation of the* 325 GHz $5_{15} \rightarrow 4_{22}$ H_2O *Maser Line*

Collisional excitation of H_2O by warm H_2 molecules can plausibly account for the observed luminosity of the 325 GHz $5_{15} \rightarrow 4_{22}$ maser emission. NM have discussed the collisional pumping of (sub-)millimeter water masers in detail, using an escape probability method to determine the equilibrium level populations of water under varying conditions of temperature, density, and water abundance. Their calculations predicted that the simultaneous inversion of, among others, the 22, 183, 321, and 325 GHz H_2O transitions can be achieved over a range of astrophysical conditions. Furthermore, NM derived values for the ratio of photon luminosities in any two maser lines, assuming that both lines are saturated and identically beamed, as a function of the temperature, hydrogen density, water abundance, and velocity gradient. Observations of various line ratios can therefore, in principle, be used to constrain the physical conditions in the masing region. In practice, of course, it is difficult to obtain meaningful line ratio estimates, since all single-dish measurements will yield only spectra representing the average emission of a large number of maser clumps, and, except for the 22 GHz line, interferometric observations of water masers are currently not possible. If nevertheless we calculate these "averaged" 325 GHz/22 GHz luminosity ratios, L_{325}/L_{22}, we find values of 0.7, 0.5, 0.8, and 0.3 for Orion-KL, IRAS 1629A, W49N, and W51 Main, respectively. These numbers are rather uncertain because of calibration uncertainties and because the 22 GHz data taken from Menten, Melnick, and Phillips (1990) for W49N and W51 Main and from unpublished data for Orion-KL were obtained several months before the 325 GHz data. In the scenario where a fast ($v \geq 50$ km s^{-1}) dissociative shock propagates in gas of density $\approx 10^7$ cm^{-3}, the water maser emission arises in the warm (≈ 400 K) region of molecule reformation behind the shock front (Elitzur, Hollenbach, and McKee 1989). For all temperatures ≥ 400 K, the calculations of NM predict that $L_{325}/L_{22} \leq 0.45$. The L_{325}/L_{22} values we quote for Orion-KL and W49N are somewhat above this limit, although given the mentioned uncertainties, the significance of these higher values is not clear. In the context of the fast shock model (Elitzur *et al.*), our detection of luminous 325 GHz maser emission implies that shocks for which $n_9^2 x_{-4}(H_2O) d_{13}/\Delta v_5 < 5$ are common, where $10^9 n_9$ is the density of hydrogen nuclei in the shocked gas (in cm^{-3}), $10^{-4} x_{-4}(H_2O)$ is the relative abundance of water molecules, and where $10^{13} d_{13}$ is the thickness (in cm) and Δv_5 is the velocity dispersion (in km s^{-1}) of the warm shocked layer.

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