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H_2O MASER EMISSION ASSOCIATED WITH T TAURI AND OTHER REGIONS OF STAR FORMATION

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ABSTRACT

We report the detection of H_2O maser emission from three new galactic regions: a point 0$'$.9 NE of T Tauri, and toward the H II regions G29.9−0.0 and G0.55−0.85. The T Tauri water source is not coincident with any known optical object; comparison of the H_2O and CO observations of this region suggests the presence of an embedded protostellar region in the molecular cloud. We have monitored these sources and those in S140–IR and Mon R2 for time variations and have found that all sources except T Tauri are time-variable on the scale of a month. A model for the varying component of Mon R2 is proposed.

Subject headings: interstellar: molecules — masers — stars: formation — stars: individual — stars: pre–main-sequence

I. INTRODUCTION

Recent work has shown that maser emission in the $6_{16} \rightarrow 5_{23}$ transition of H_2O is often closely allied to the star formation process, as evidenced by the proximity of many of the maser sources to infrared sources, compact H II regions, and Herbig-Haro objects embedded in molecular cloud complexes (e.g., Sullivan 1973; Lo, Burke, and Haschick 1975; Cato *et al.* 1975). To improve our understanding of the relation of H_2O masers to prestellar evolution, we have begun a program of searching for new H_2O maser sources in various young objects, and of monitoring several maser sources for time variability (Morris and Knapp 1976, hereafter Paper I). By measuring time variations of maser emission from objects having relatively simple H_2O spectra, one has a potentially powerful means of determining the source structure and the excitation mechanism for the water molecules.

In the present paper, we describe three new galactic H_2O maser sources, one of which is associated with the pre–main-sequence star T Tau. We also describe monitoring observations of these and two other sources, S140-IR and Mon R2 (Paper I). In Mon R2, a rapidly varying maser with unusual characteristics is present at the molecular cloud velocity; we propose that this maser is pumped by near-infrared photons emanating from a pre–main-sequence star or a protostar.

II. OBSERVATIONS

The observations were made in several sessions during 1975 July–September, with the 40 m telescope of the Owens Valley Radio Observatory, the NRAO 22–24 GHz receiver, and a 100 channel autocorrelation spectral line receiver. The system parameters and observing techniques are as given in Paper I; the telescope gives ~9 jansky per kelvin at this frequency. The regions chosen were observed with a velocity range $\sim \pm 50$ km s^{-1} around the systematic velocity of each source. The detected sources are discussed in the following section; the undetected sources are listed in Table 1.

III. RESULTS: DISCUSSION OF INDIVIDUAL SOURCES

a) *T Tauri*

This is a particularly interesting maser emission source: it is the first source to be found in a young region within which there are no previously known infrared or compact radio sources. The H_2O spectrum (Fig. 1) consists of a single component at a velocity of $+1.4$ km s^{-1}. No significant time variations occurred between 1975 July 3 and 1975 September 30,

TABLE 1

POSITIONS OF SOURCES SEARCHED FOR H_2O MASER EMISSION WITH NEGATIVE RESULTS

Source	α(1950)	δ(1950)
S222*	$04^h26^m59^s$	+35°10′42″
S239†	04 28 25	+18 00 51
IC 2087	04 36 49	+25 39 10
NGC 1788	05 04 22	−03 23 31
NGC 1999	05 34 03	−06 44 50
IC 430	05 35 55	−07 04 36
NGC 2023	05 39 07	−02 16 58
M78 No. 1	05 44 08	+00 08 00
M78 No. 2	05 44 40	+00 16 00
M78 No. 3	05 43 36	−00 12 00
NGC 2264	06 38 24	+09 32 06
IC 2177	07 02 04	−10 22 09
ρ Oph	16 23 10	−24 18 20
CD −42°11721–IR	16 50 13	−42 25 12
H2-3	17 06 02	−41 32 17
NGC 6357	17 21 24	−34 08 24
R CrA No. 1	18 58 32	−37 02 08
R CrA No. 2	18 58 29	−37 01 10
CRL 2688	21 00 20	+36 29 45

* Observations made on a grid ~5′ NS × 2′ EW.
† Observations made on a line ~6′ EW.

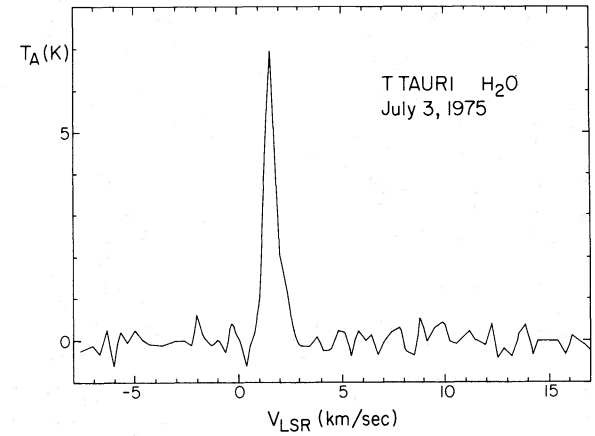

FIG. 1.—H_2O maser near T Tauri. The ordinate is antenna temperature on the 40 m OVRO telescope, and the abscissa is radial velocity with respect to the local standard of rest.

in contrast to all other sources discussed in this paper. We have determined the position of the maser to be $\alpha = 04^h19^m06^s$, $\delta = +19°25'50'' \pm 30''$ (1950); thus the maser source is displaced by $\sim 0'.9$ from the position of T Tauri and so is unlikely to be directly associated with the star itself. A sketch of the region, showing the H_2O source position, is shown in Figure 2. There is no obvious optical object at the position of the maser.

T Tauri appears on the face of a small dust cloud, and has several bright nebulae associated with it, including the reflection nebula NGC 1555 and the smaller emission nebula, Burnham's nebula, which has a radial velocity of $+1.4(\pm 2)$ km s^{-1} (Schwartz 1975). Further, ^{12}CO observations of the region (Knapp *et al.* 1976*b*) show two velocity components: a relatively bright, narrow feature at $+8$ km s^{-1} associated with the dust cloud and a more localized component centered at $+5$ km s^{-1} with a width of ~ 7 km s^{-1}. The extreme negative velocity of this component is at $\sim +1.3$ km s^{-1}; its shape is strongly suggestive of systematic collapse (or expansion) motions in this part of the cloud (Knapp *et al.* 1976*b*). If the H_2O maser is formed by amplification of 22 GHz continuum photons from some central source, then the H_2O and CO observations suggest outward motions of the gas around the central object. If so, the H_2O maser is formed along the line of sight roughly through the center of the cloud. Infrared and radio continuum observations of this region are of great interest for investigating the possible presence of an embedded central object.

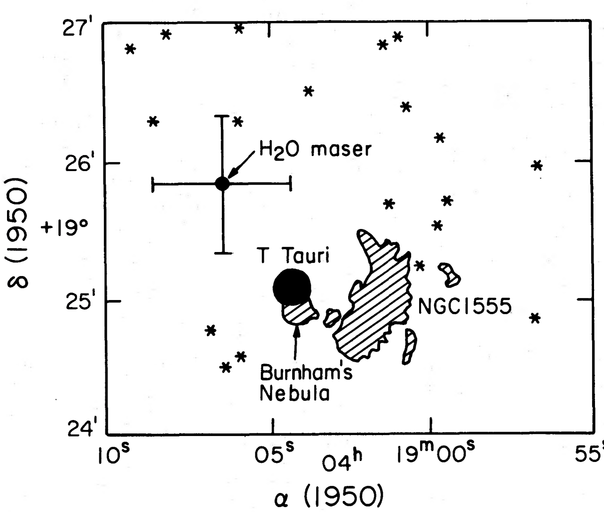

FIG. 2.—Position of the T Tauri H_2O maser superposed on a sketch of the region (Schwartz 1975). NGC 1555 (Hind's nebula) is a reflection nebula illuminated by T Tau; Burnham's nebula is an emission nebula.

b) *G0.55−0.85*

This is a small H II region also known as RCW 142; observations of H_2CO and OH toward this source have shown the presence of Type I (main line) OH maser emission, with the OH satellite lines and the H_2CO seen in absorption (Gardner and Whiteoak 1975). We detected H_2O maser emission from this source on 1975 July 3 and made subsequent observations on September 1 and October 1. Two of the resulting spectra are shown in Figure 3. A total range of ± 60 km s^{-1} around the source velocity ($+13$ km s^{-1}) was searched for maser emission. Initially, four components were found; a weak feature at $+2.4$ km s^{-1} and stronger features, partially blended, at $+13.1$, $+14.3$, and $+17.7$ km s^{-1}. The OH and H_2CO absorption appear over the velocity range of the stronger components; there is an apparent velocity

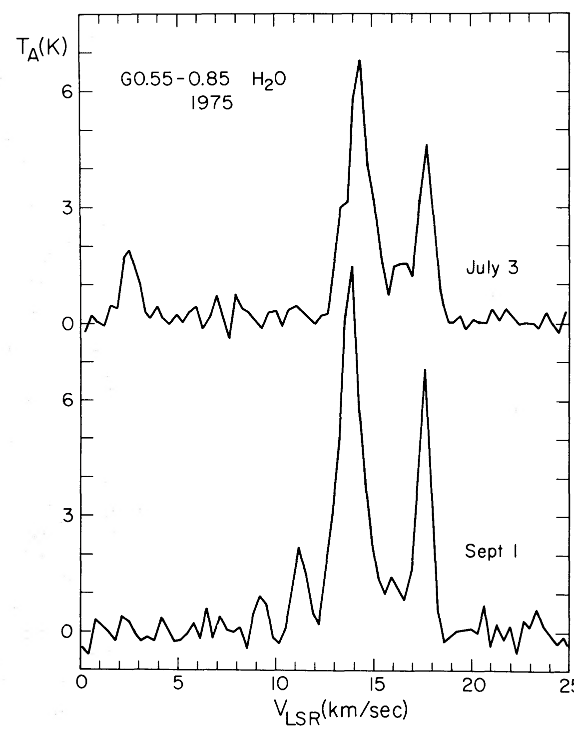

FIG. 3.—Spectra of H_2O emission from G0.55−0.85

correspondence between the 1665 MHz maser and the H_2O maser, but none between the H_2O and 1667 MHz masers. Time variations in several velocity components are evident in Figure 3; the strongest component appears to have shifted from 14.3 to 13.8 km s^{-1} in the 2 month interval, which indicates that this feature is probably a blend of at least two varying components. The position of the H_2O maser is $\alpha = 17^h47^m05^s$, $\delta = -28°54'36'' \pm 30''$ (1950), or about 2′ from the position of the continuum peak given by Gardner and Whiteoak (1975).

c) *G29.9−0.0*

This is the third H_2O maser source to be found in the W43 complex (Cato *et al.* 1975). The compact H II region G29.9−0.0 was first studied by Felli, Tofani, and D'Addario (1974) in the course of their 2.8 cm survey of radio fine structure in H II regions. Subsequently, Soifer and Pipher (1975) performed a detailed study of this object at infrared wavelengths. The maser source is coincident with the peak 12.6 μ position [$\alpha(1950) = 18^h43^m27\overset{s}{.}7$, $\delta(1950) = -02°42'48''$] to within 30″. The spectrum is shown in Figure 4; no other features than those shown were found between 55 and 138 km s^{-1} to a limit of 1 K. A spectrum observed 1 month later shows variations typical of H II region H_2O sources.

d) *Sharpless 140*

The detection of H_2O maser emission from this source at ~ -15 km s^{-1} was reported in Paper I. Since then, we have monitored the source approximately once a month, and have searched for further velocity components. Several new components have been found, including a very strong one at $+9.7$ km s^{-1}. All of the components, except the $+9.7$ km s^{-1} component have shown significant variations with time. Spectra observed between 1975 July 3 and September 30 are shown in Figure 5. All of the components are colocated (at the position of the infrared source: Blair and Vanden Bout 1974) to within $\sim 30''$.

Except for the $+9.7$ km s^{-1} feature, the radial velocities of H_2O features in this source appear to cluster more or less symmetrically about the molecular cloud velocity. These H_2O features between -5.2 and -15.7 km s^{-1} all lie approximately within the radial velocity range over which CO emission is present in this direction (-3 to -15 km s^{-1}; Knapp *et al.* 1976*b*). If each of these features is associated with a protostellar condensation, then the velocity spread around the mean cloud velocity is consistent with the dispersion expected for a region containing a moderate mass in gas and stars. In this case, the sources of the individual H_2O features would be spatially distributed over a sizable region ($\gtrsim 5''$) as is the case with H_2O features in Orion A (Hills *et al.* 1972). The weakness of the emission has so far prevented a determination of the small-scale spatial distribution of the H_2O components.

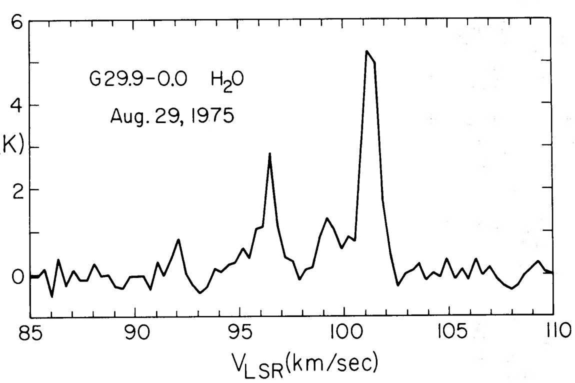

FIG. 4.—Spectrum of H_2O emission from G29.9−0.0

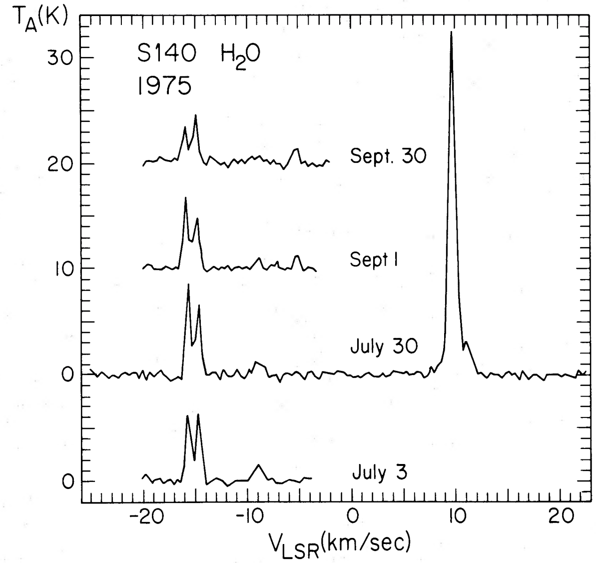

FIG. 5.—Spectra of H_2O emission from S140–IR, showing time variations in the features near the molecular cloud velocity.

The $+9.7$ km s^{-1} feature is somewhat anomalous; the fact that the most intense feature is $+19$ km s^{-1} away from the molecular cloud velocity (and the velocity centroid of the other H_2O features) is difficult to explain. Usually, such "high-velocity" features are much less intense than the H_2O features near the molecular cloud velocity. Neglecting the possibility that a late-type star with a characteristic expanding envelope is embedded in the molecular cloud at this position, we know of no source having H_2O emission characteristics similar to S140. An accurate position determination for the $+9.7$ km s^{-1} feature would be helpful; if it is coincident with the infrared source, then a strong case could be made for rapidly infalling molecular gas onto a protostellar object.

e) *Monoceros R2*

The Mon R2 reflection nebula association has received much observational attention recently; it is an active site of star formation, containing a dense molecular cloud (Loren, Peters, and Vanden Bout 1974; Kutner and Tucker 1975), a cluster of infrared objects (Beckwith *et al.* 1976), a compact H II region (Brown, Knapp, and Kuiper 1975; Downes *et al.* 1975), and OH and H_2O masers (Knapp and Brown 1976; Paper I). Our subsequent monitoring of the maser source has shown that the $+12$ km s^{-1} component is always present and shows little, if any, variation in time, while the "$+10$ km s^{-1}" component appears and disappears repeatedly, sometimes within a week. Also, the peak velocity of the "$+10$ km s^{-1}" component has shifted slightly from 10.4 km s^{-1} in 1975 May (Paper I) to 9.5 km s^{-1} in 1975 July and August. In Figure 6, we present the peak strength of the "$+10$ km s^{-1}" component (expressed as a fraction of the strength of the $+12$ km s^{-1} component), plotted as a function of time. Some of the H_2O spectra observed for this source are presented in Paper I. The fastest variation occurred between days 180–190, when the source appeared and disappeared in ~ 8 days. Typically, the source is either present at a level of 30–40 Jy or absent ($<$5–10 Jy). The variations appear to be irregular; simple periodic variations are not supported by our data. Although essentially all components of all water-vapor maser spectra are time-variable (e.g., Sullivan 1973), the particular type of behavior evinced by Mon R2, *viz.*, the repeated and rapid appearance and disappearance of maser radiation at a nearly constant velocity has not been heretofore described in the literature.

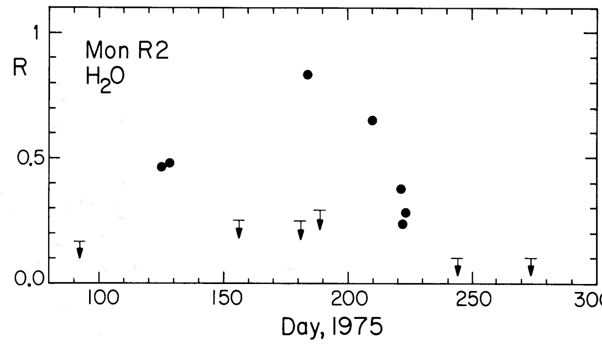

FIG. 6.—Time variations in the "$+10$ km s^{-1}" maser component in Monoceros R2. The intensity is expressed as a fraction of the intensity of the $+12$ km s^{-1} component.

A physical interpretation of this flickering maser component must account for (1) the capability of this component to appear or disappear in $\leqslant 3$ days, (2) the irregular recurrence of this component at a nearly constant velocity, (3) the fact that the intensity of this component is the same to within a factor of 2 at each recurrence, and possibly (4) the coincidence in velocity between the varying maser component and the central molecular cloud of the Mon R2 complex (Kutner and Tucker 1975). The short time scale for variations is explained most satisfactorily if the H_2O molecules are pumped by an external source of near-infrared photons which itself varies rapidly with time. Among the infrared sources found by Beckwith *et al.* (1976) in Mon R2, IRS 3 and possibly IRS 2 produce a large enough near-infrared flux to account for the H_2O maser radiation via this mechanism according to the thermodynamic arguments presented by Goldreich and Kwan (1974). Other infrared sources in this complex might also be adequate if the extinction along the line of sight to them is large in the near-infrared. A near-infrared source which undergoes such rapid intensity variations must be fairly compact (i.e., of protostellar dimensions). Furthermore, the maser cloud must either surround the infrared source or be quite close to it if full advantage is to be taken of the available supply of infrared photons.

The fluctuations required of the external near-infrared source are reminiscent of those observed for some pre–main-sequence stars (e.g., Kuhi 1964; Cohen 1973). However, typical pre–main-sequence stars like T Tauri are probably not luminous enough in the near-infrared to provide the necessary pump photons (e.g., T Tau emits $\sim 10^{42}$ 6.3 μ photons per second in a 3 km s^{-1} velocity range, compared with the isotropic microwave photon emission rate of the "10 km s^{-1}" H_2O maser, which is typically $\sim 10^{43}$ photons per second when this feature is present). Thus if the source of near-infrared photons is a pre–main-sequence object, it should be more luminous than T Tau by at least an order of magnitude, and in addition should show rapid intensity variations.

Beckwith *et al.* (1976) have suggested that the compact H II region seen in this direction lies behind at least part of the infrared cluster, while Downes *et al.* (1975) have found extended ($\sim 2'$) radio continuum emission underlying the region. Thus it appears possible that a background source of 1.3 cm photons is present for all of the known infrared objects, and that this background is amplified by the inverted H_2O molecules to produce the observed emission.

Finally, we note that this model predicts that the Mon R2 complex contains at least one infrared object which is variable at near-infrared wavelengths (although this object may be heavily obscured). Furthermore, it is unlikely that the $+10$ km s^{-1} maser line will ever be much more intense than has already been observed. We cannot at present offer an explanation for the apparent tendency of the $+10$ km s^{-1} component to have an approximately constant intensity whenever it is detectable. Further work is in progress to determine the actual range of intensity of this component, and to search for periodicities and/or very weak emission at this velocity.

f) *Negative Results*

In addition to the regions discussed herein, and in Paper I, we have searched others without success, usually over a range of $\sim \pm 45$ km s^{-1} around the central velocity, and to a sensitivity of $\sim$10–20 Jy. The observed regions are listed in Table 1.

IV. CONCLUSIONS

Of the six masers found in star-formation regions which are discussed in the present work and in Paper I, all are associated with molecular clouds, and all (except for G0.55$-$0.85 and T Tau, for which the information does not yet exist) are associated with infrared sources. However, some of the regions (S140–IR, OMC-2 [Paper I]) have no compact radio component at the H_2O maser position. We emphasize the previous conclusion that conditions can be suitable for the existence of H_2O masers *before* any early-type stars have evolved to the stage where compact H II regions form (Lo, Burke, and Haschick 1975; Paper I).

The spectral characteristics of S140 and Mon R2 have allowed rough models of the maser-emitting regions to be constructed. In particular, the flickering H_2O line in Mon R2, which exhibits a new type of phenomenon amongst H_2O masers, appears to be formed in the local molecular gas surrounding a strong, variable source of near-infrared photons. The analysis strongly suggests that this object is a protostar or a dust-enveloped pre–main-sequence star. Further refinement of these models will be aided considerably by better position determinations.

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