Water Masers in the Circumstellar Environments of Young Stellar Objects

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ABSTRACT

We present a high resolution radio and millimeter wavelength study of five, low-mass, young stellar objects with known water maser emission: RNO15FIR, Orion A-W, L1157, B361, and L1251A. These objects are cold IRAS sources with far-infrared luminosities ranging from <6 to 40 $L_\odot$. Radio continuum observations are used to locate precisely the young stellar object(s) responsible for the far-infrared emission and to investigate their relationship to the water masers and tracers of their stellar winds. Compact radio continuum emission was detected within the IRAS error ellipse for Orion A-W, L1157, and L1251A; the spectral indices of their radio emission are consistent with thermal ionized winds. High resolution VLA H_2O observations located pairs of masers associated these radio sources within projected distances of 50 AU, 235 AU, and 150 AU, respectively, clearly placing these masers in the circumstellar environments of the young stellar objects. In Orion A-W, the strongest maser feature was used to self-calibrate the line and continuum data, resulting in the detection of a λ=1.3 cm continuum source offset 50$\pm$17 AU from the strongest maser. Due in part to the small separations of the masers and continuum sources, none of the masers could be identified with gravitationally unbound motions expected for a stellar wind origin.

Subject headings: stars: pre-main-sequence, circumstellar matter – masers – radio continuum: stars – ISM: jets and outflows

1. Introduction

Water maser emission is a common feature of deeply embedded young stellar objects (YSOs). These YSOs have Class 0 or Class I spectral energy distributions that rise steeply at far-infrared wavelengths with little or no emission at near-infrared wavelengths, indicative of extensive circumstellar dust (Lada 1991; André 1995). A recent survey of a sample of Class 0/Class I sources identified by the Infrared Astronomical Satellite (IRAS) has revealed that H_2O maser activity is common in YSOs with $L<120L_\odot$, with 24 of the study's original 42 objects displaying highly variable H_2O maser emission (Wilking *et al.* 1994; Claussen *et al.* 1996). The low-to-intermediate luminosity of these YSOs implies a low mass for the central object ($<3M_\odot$). For low mass YSOs, unlike massive stars, maser activity appears to be concentrated within several hundred AU of the YSO (Wootten 1989; Terebey, Vogel, & Myers 1992; Chernin 1995).

The presence of water maser emission from the $6_{16} \rightarrow 5_{23}$ transition at 22 GHz is well-correlated with the presence of high velocity molecular gas and appears to be another indicator of mass loss in YSOs (Felli *et al.* 1992; Wilking *et al.* 1994). This suggests that water masers arise in dense shock fronts created by the interaction of a strong stellar wind with circumstellar or ambient cloud material (Elitzur, Hollenbach, and McKee 1989). This maser emission may be produced by a combination of low velocity, non-dissociative shocks (C shocks, $v<40$ km sec^{-1}) or fast, dissociative shocks (J-shocks); non-dissociative shock models are more efficient in exciting maser emission and better at explaining higher frequency water maser emission (Kaufman and Neufeld 1996). Alternatively, models of infalling gas onto protostars have shown that water maser emission in low-to-intermediate luminosity YSOs may be excited in accretion (Ceccarelli, Hollenbach, and Tielens 1996).

Ultimately, high resolution studies that reveal the positions and space velocities of masers relative to the YSOs can distinguish between outflow or infall models for maser emission. For example, VLA observations of the water masers associated with the cold YSO L1448C show that the masers are well-aligned with the highly collimated molecular outflow and their velocities are too high to arise in a Keplerian disk (Chernin 1995). Outflow excitation is also suspected for water masers found toward two YSOs in the Ophiuchus cloud: YLW 16A and southern component of the protobinary system IRAS 16293-2422 (Terebey *et al.* 1992; Wootten 1989). While evidence for maser excitation via a disk/wind interaction or infall has not been found in low-to-intermediate luminosity YSOs, they have been suggested for higher luminosity YSOs. For example, SiO masers in Orion IRc2 have been modeled as arising in a rotating and expanding disk (Plambeck, Wright, & Carlstrom 1990). A disk origin for water masers has also been proposed for the luminous YSO IRAS 0038+6312 (Fiebig *et al.* 1996).

In this study, we present high resolution observations for five Class 0/Class I YSOs taken from the Claussen *et al.* (1996) study. These observations are part of a larger VLA study to investigate water maser emission from low-to-intermediate luminosity YSOs (Wootten *et al.* 1998). The positions and properties of the five sources are presented in Table 1. All sources are known to display H_2O maser emission, and all but one is associated with a molecular outflow. Prior to our study, the locations of the YSO inside the IRAS error ellipse were largely unknown. Our main motivation is to locate precisely the YSO responsible for the far-infrared emission by detecting the radio continuum emission and associated H_2O maser activity. The radio continuum observations detect free-free emission due to either the stellar wind or an accretion shock, thus providing the location of the YSO. In the past, single dish studies had insufficient resolution to locate the radio sources or masers relative to the IRAS position, near-infrared sources, or other signs of mass loss. Our ultimate goal, after locating the YSO and its surrounding features, is to investigate the origin of the water maser emission.

2. Observations

High resolution observations in the millimeter and centimeter continuum, the J=1→0 transition of CO, and the $6_{16}\rightarrow5_{23}$ transition of H_2O were made for five YSOs with known H_2O maser emission. The frequencies of the continuum observations were 4.86 GHz, 8.46 GHz, 22.255 GHz, and 107.1 GHz, henceforth referred to as λ=6 cm, 3.6 cm, 1.3 cm, and 2.8 mm. Centimeter continuum observations of L1251A, L1157, Orion A-W, RNO15FIR, and B361, and H_2O $6_{16}\rightarrow5_{23}$ observations of L1251A, L1157, and Orion A-W, were obtained using the NRAO Very Large Array (VLA) [1] . The millimeter continuum observations for L1157 and L1251A and observations of the CO (J=1→0) transition for L1251A were made with the BIMA Array [2] . The observations are summarized in Table 2. The details of the observing mode are given in columns (3)-(10), including the frequency (column 4), the instrument and configuration (column 5), the total bandwidth (column 6), the velocity resolution for spectral line mode (column 7), the field of view (column 8), and the synthesized beam size and position angle east of north (columns 9 & 10). The amplitude and phase calibrators and their respective flux densities are given in columns (11) and (12). RMS noises for continuum and spectral line observations are found in Tables 3 and 4, respectively.

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[1]The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

[2]The BIMA Array is operated by the Berkeley-Illinois-Maryland Association under funding from the National Science Foundation.

2.1. Data Reduction

Calibrations of VLA line and continuum data were done using the CLCAL task in the AIPS [3] package. Standard amplitude calibrators were used to bootstrap the fluxes for phase calibrators for all VLA observations (with the exception of those taken in August 1994). An error in the observing configuration for the August 1994 program led to a spectrum of L1251A with only the channels red-shifted from the ambient cloud velocity. Also, in lieu of an amplitude calibrator for L1251A, a May 1994 observation of the radio source 0333+321 was used with its bootstrapped flux of 1.25 Jy. For all continuum data, phase errors of more than 20° and amplitude errors of more than 20% were flagged and excluded from the calibration.

The strong (210 Jy beam^{-1}) water maser in Orion A-W was used to self-calibrate both the spectral line and λ=1.3 cm continuum data for this source. Using the CALIB task in AIPS, several iterations were performed, with the last solution solving for both amplitude and phase. As a result of applying the new solutions to the simultaneous observations of the λ=1.3 cm continuum and water maser lines, the RMS noise improved in the spectral channel map from 0.96 to 0.12 mJy beam^{-1} and in the continuum channel from 1.1 to 0.52 mJy beam^{-1}.

All datasets from the BIMA Array were calibrated using the MIRIAD[4] software. Analysis of the calibrated data was done using AIPS software. The fluxes of the phase calibrators were bootstrapped from the primary calibrator W3(OH).

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[3] Astronomical Image Processing Software

[4] Multichannel Image Reconstruction, Image Analysis, and Display software developed by the Berkeley, Illinois, and Maryland Association.

2.2. Positional Uncertainties

Absolute positional uncertainties were estimated for each set of observations in the following way. For the VLA data, the larger of the two following values was used: $\pm0.1''$ or ±0.1 times the synthesized beam size projected onto the RA and DEC axes. The error of $\pm0.1''$ is set by uncertainties in the reference frame of the phase calibrators. An error of ±0.1 times the synthesized beam is valid if phase errors $>36°$ are excluded, as is the case of our continuum data. For the BIMA data, absolute positions are estimated to be ±0.2 times the synthesized beam. Absolute positional errors for source positions in RA and DEC are presented in columns (9) and (11) of Tables 3 and 4.

In cases where multiple sources were detected in a single observation, the relative positional error can be estimated from the astrometric resolution of each source. The astrometric resolution of a source is given by $\theta_b/2(\mathrm{S/N})$, where θ_b is the synthesized beam diameter and S/N is the signal-to-noise. The relative positional error between two sources is determined largely by the astrometric resolution of the source with the lowest S/N. When relevant, the astrometric resolution is given in parenthesis for the last digits in the RA seconds and the DEC arcseconds in columns (8) and (10) of Tables 3 and 4.

3. Results and Analysis

A summary of the IRAS positions and properties for our sample is given in Table 1. Continuum detections near the IRAS position are listed in Table 3, as well as detections outside of the IRAS error ellipse but still within the λ=3.6 cm primary beam. All continuum sources were unresolved and hence only their peak flux densities are given in Table 3. For sources detected in two centimeter continuum bands, the spectral index α is calculated, assuming the emission varies as ν^{α}. Spectral line detections are listed in Table 4. Each of our sources, except B361, has been imaged at λ=2.1 μm by Hodapp (1994). The following sections discuss the sources individually.

3.1. IRAS 03245+3002 (RNO15FIR or L1455 IRS 1)

RNO15FIR lies in the L1455 dark cloud. A λ=2 μm source has been found displaying positional and spectral properties that suggest it corresponds to the far-infrared source (Ladd *et al.* 1993; Hodapp 1994; Persi *et al.* 1994; Tapia *et al.* 1997). Using these combined data, Tapia *et al.* derived a spectral energy distribution typical of an extreme Class I object with a dust temperature of T_D=42 K. Strong H_2O maser activity (as seen in single-dish observations), [SII] emission knots, and a collimated molecular outflow and jet trace the energetic wind from RNO15FIR (Bally *et al.* 1997; Davis *et al.* 1997a, 1997b; Tapia *et al.* 1997).

Despite its association with signs of mass loss, we detected no centimeter emission at the IRAS position. The 3 sigma upper limits for the emission are 0.12 mJy beam^{-1} and 0.24 mJy beam^{-1} at λ=3.6 and 6 cm, respectively. Our λ=6 cm upper limit is consistent with the upper limit of 0.5 mJy beam^{-1} established by Schwartz *et al.* (1985) at the same wavelength. Three non-thermal sources were detected in the field which are probably extragalactic in origin (Table 3). The λ=3.6 cm and λ=6 cm detections of our sources B and C confirm the double non-thermal source seen by Schwartz *et al.* (1985).

3.2. IRAS 05302-0537 (Orion A-W)

Orion A-W is a Class I YSO associated with a molecular outflow (Fukui 1989). Fairly weak H_2O maser activity, that appears to be highly variable, has been detected by several groups. Felli *et al.* (1992), Tofani *et al.* (1995), and Claussen *et al.* (1996) have reported detections over several years of observations, with velocities of 0 km s^{-1}, 8 km s^{-1}, and 14 km s^{-1}. Tofani *et al.* (1995) also have reported the detection of an extended source (0.53$''$ x 0.43$''$) at the IRAS position at λ=3.6 cm using the VLA in A configuration.

As seen in Table 3, we have detected an unresolved source at the IRAS position in the λ=1.3 and 3.6 cm bands. Our λ=3.6 cm flux (0.92 mJy beam^{-1}) is very comparable to the integrated flux measured by Tofani *et al.* The spectral index is 1.15$\pm$0.19, consistent with thermal emission. Unusually strong maser emission was observed in April 1997 with a peak flux of 210 Jy beam^{-1} from a blue-shifted component at 3.7 km s^{-1}. A second, red-shifted component was observed with a peak flux of 15.4 Jy beam^{-1} at 9.6 km s^{-1}. Within our absolute positional uncertainties ($\pm$0.1$''$), the masers and continuum source are coincident and at the same position reported by Tofani *et al.* However, the relative positions of the λ=1.3 cm continuum and water maser sources are much better determined and, as shown in Fig. 1, have significant offsets. In particular, the strongest maser feature is offset from the λ=1.3 cm continuum source at the 3σ level (0.04$\pm$0.03$''$ west and 0.10$\pm$0.04$''$ north) and from the weaker maser component at the >100σ level (0.0588$\pm$0.0002$''$ west and 0.0848$\pm$0.0003$''$ north). At the distance of Orion A-W, the strong maser is offset by about 50 AU from the continuum source and weaker maser. Fig. 1 shows the locations of the masers and the λ=1.3 cm continuum source relative to the IRAS position.

3.3. IRAS 20386+6751 (L1157)

This deeply embedded YSO in the L1157 cloud shows several signs of mass loss consistent with being a very young, possibly Class 0, object. It has only recently displayed H_2O maser activity (since 1996), as reported by Claussen *et al.* (1996). It lies at the center of a highly collimated CO outflow with associated clumpy SiO and molecular hydrogen emission (Zhang *et al.* 1995; Davis & Eislöffel 1995). The outflow lies nearly in the plane of the sky (i$\sim$80°, Gueth *et al.* 1996). The blue-shifted CO outflow shows evidence for strong interaction between the stellar wind and ambient gas. CH_3OH emission is also present in the bipolar outflow, displaying profiles similar to other lines tracing the shocked molecular material (Bachiller *et al.* 1995). Gueth *et al.* (1996) have reported high resolution ^{12}CO observations of two limb-brightened cavities which they propose may be created by large bow shocks due to a precessing, highly collimated jet. Further evidence of stellar winds comes from observed ammonia emission which may also trace bow shocks (Tafalla and Bachiller 1995).

As seen in Table 3, we have detected a point source at λ=3.6 and 6 cm within the IRAS error ellipse (Fig. 2). The spectral index of this radio source, 0.3 ± 0.4, is consistent with thermal emission. Two non-thermal sources, most likely extragalactic in origin, were also observed in the field and are listed in Table 3.

A resolved continuum source was detected at λ=2.8 mm with the BIMA Array (Table 3). The source is within the IRAS error ellipse and offset at the 1.5σ level, east and south of the λ=3.6 cm source. However, we do not regard this offset as statistically significant. The peak λ=2.8 mm flux of 36 mJy beam^{-1} is in excellent agreement with the λ=2.7 mm measurement by Gueth *et al.* (1997) using the IRAM interferometer. The emission appears extended with an integrated flux of 64 mJy and a deconvolved source size of 4.8$''$ x 3.5$''$ along a position angle of 146°. The elongation of the source is in direction of the outflow axis (PA$\sim$155°) as noted by Gueth *et al.*

In Fig. 2, the positions of the centimeter, millimeter, and maser detections are plotted, as well as the IRAS position and error ellipse. The H_2 (B1) position corresponds to the molecular hydrogen knot B1 from Davis and Eislöffel (1995). The dotted line shows the position angle of the outflow as defined by H_2 knots A1 and C1 (Davis and Eislöffel 1995). The H_2O masers and the centimeter source appear coincident to within their 2σ positional uncertainties (<235 AU).

The spectral energy distribution shown of IRAS 20386+6751 (Fig. 3) shows that the millimeter continuum emission arises from cold dust with a temperature of $\sim$ 45 K. This spectral energy distribution is characteristic of extreme Class I or Class 0 sources, with no detected emission at λ<25 μm. The bolometric luminosity of the source is estimated to be 10 $L_\odot$. We can estimate the mass of gas and dust from the λ=2.8 mm emission by assuming a constant temperature of 45 K and a dust mass opacity of κ=0.1(0.25/λ_{mm})$^\beta$. Using the integrated flux, the estimates for the total mass vary from 0.5 $M_\odot$ to 1.6 $M_\odot$ as β varies from 1.0 to 1.5. The strength of the compact λ=2.8 mm emission compared to the bolometric luminosity solidifies the classification of L1157 as a Class 0 source. This relative strength implies a high ratio of circumstellar to stellar mass which is a signpost of objects in the accretion phase of evolution. Following André (1995), we can estimate the ratio $S_{2.7mm}{}^{peak}$(mJy)(d/160)^2/L_{bol} for L1157 and several prototypical Class 0 sources. For L1157, this quantity is 25 mJy/$L_\odot$ compared to 17 mJy/$L_\odot$ for the combined IRAS 16293-2422 protobinary (Mundy *et al.* 1992), 24 mJy/$L_\odot$ for B335 (Chandler and Sargent 1993), and 100 mJy/$L_\odot$ for VLA1623 (André, Ward-Thompson, and Barsony 1993).

3.4. IRAS 21106+4712 (B361)

B361 contains a low luminosity Class I YSO which has displayed a single, weak H_2O maser (Claussen *et al.* 1996). This source is the only region included in this paper that has no known molecular outflow. The lack of a molecular outflow is based on the absence of broad wings in the CO (J=1$\rightarrow$0) profiles observed toward the IRAS position (Wouterloot and Brand 1989). However, given the high correlation between masers and molecular outflows, it is expected that high sensitivity CO mapping of the source will reveal an outflow. Our observations in the radio continuum yielded upper limits for both the λ=3.6

and 6 cm bands which are presented in Table 3.

3.5. IRAS 22343+7501 (L1251A)

This IRAS source in the L1251A cloud is associated with a cluster of near-infrared sources spread over a $10''$ x $10''$ area (Rosvick and Davidge 1995). Millimeter continuum emission at λ=1.3, 1.1, and 0.85 mm has been detected from the cluster using the JCMT (Rosvick and Davidge 1995). Signs of stellar outflows in this area include an optical jet (Balázs *et al.* 1992) and a large scale bipolar molecular CO outflow (Sato and Fukui 1989). The source has also displayed a strong, single-velocity H_2O maser at 4 km s^{-1} as seen by Claussen *et al.* (1996) and a weak H_2O maser at $\sim$3 km s^{-1} as seen by Tóth and Walmsley (1994) and Claussen *et al.* (1996). In this paper, we will refer to the five near-infrared sources labeled A-E by Rosvick and Davidge as RD-A - RD-E. Based upon its red infrared color from J (λ=1.25 μm) to K$'$ (λ=2.11 μm), they associate the brightest K$'$ source, RD-A, with the IRAS source.

As shown in Fig. 4, only two of the near-infrared sources were detected in our radio continuum observations. Although Rosvick and Davidge do not provide accurate absolute positions, the relative positions of their sources RD-A and RD-D are identical to our VLA sources B and A, respectively (Table 3). Both VLA sources lie within the IRAS error ellipse (Fig. 5) and have spectral indices consistent with thermal emission. However, our observations suggest that RD-A may not be the YSO primarily responsible for the far-infrared emission. Not only is the radio continuum emission from RD-D stronger, but the water maser emission is nearly coincident with RD-D (Table 4). Given these properties and its large value of (J-K), RD-D may be the major contributor to the far-infrared flux. Ultimately, the relative contribution of these YSOs to the IRAS flux densities can be determined from high resolution mid-infrared or submillimeter imaging. Unfortunately, our

BIMA observations failed to detect either source; the 3 sigma upper limit to the λ=2.8mm flux densities for VLA sources A and B was 12 mJy beam^{-1}.

In addition to the VLA sources corresponding to RD-A and RD-D, we detected two radio sources, D and E, outside of the IRAS error ellipse which are possible thermal sources associated with YSOs (Table 3). While they correspond to no known near-infrared, IRAS, or Hα emission-line sources (Kun and Prusti 1993), we cannot rule out that they are associated with low-luminosity YSOs in the L1251 cloud. VLA radio source C is a non-thermal source that lies just outside of the IRAS error ellipse and is most likely a background source (Table 3).

Two water masers were detected in our A array observation and associated with cm(A). The masers are coincident with each other to within twice the astrometric resolution of the weaker source which is 0.03″ or 6 AU. They are coincident with cm(A) to within their mutual 2σ uncertainties (<150 AU). High velocity CO emission was detected with the BIMA Array about midway between RD-A and RD-D. The emission is blue-shifted by 16-17 km s^{-1} from the ambient cloud velocity (Table 4). Given the association of cm(A)/RD-D with H_2O masers, one is tempted to assign the high velocity gas to it as well. The position of the CO emission is shown in Fig. 5 relative to the cm and H_2O detections, as well as the IRAS position and error ellipse.

4. Nature of the Radio Continuum Emission

Radio continuum emission is common toward low-to-intermediate luminosity YSOs and characterized by a power law spectral distribution, $S_\nu \propto \nu^\alpha$. Several mechanisms have been forwarded to explain this emission. The first is thermal emission from an ionized, spherically symmetric stellar wind; such emission has a spectral index of α=0.6 (Panagia and Felli 1975; Panagia 1991). Consideration of non-spherical outflows, adiabatic cooling, velocity gradients, and recombination can affect stellar wind emission and models of such effects predict spectral indices ranging from α=0.25-1.1 (Reynolds 1986). Stellar wind models have been criticized because they predict too much radio flux from sources which are extended on scales of a few arcseconds (Curiel *et al.* 1989). A second mechanism has been proposed in which a largely neutral stellar wind collisionally ionizes dense circumstellar material (Torrelles *et al.* 1985). In this case, the extended radio emission arises from an optically-thin, post-shock HII region with an expected spectral index of α=-0.1. This latter mechanism is consistent with the observed correlation between the radio continuum luminosity and the CO outflow momentum flux (Rodriguez *et al.* 1989). Shock-ionization models still have problems, however. The spectral index for the radio emission from many low-luminosity YSOs is much larger than -0.1, suggesting the emission is partially optically-thick. In this case, shock-ionization models only work if the emission regions are extremely compact, with radii on the order of 10 AU (Villuendas *et al.* 1996). A third mechanism, relevant to YSOs in the earliest phase of evolution, involves ionization from extreme ultraviolet radiation and collisions produced in an accretion shock in the inner regions of a circumstellar disk (Neufeld & Hollenbach 1996). Such emission would be compact and partially optically thick with a spectral index near 2. To attain the required degree of ionization, stellar masses must be at least 3.5-4 $M_\odot$ which implies that the YSOs in our sample would be underluminous relative to their eventual main sequence luminosities.

The spectral indices for the sources associated with IRAS emission - Orion A-W (A), L1157 (A), and L1251A (A & B) - vary between α=0.19 and 1.15, consistent with predictions of ionized stellar wind models. Yet our radio continuum data are not able to rule out other mechanisms because the weakness of the emission does not constrain precisely the spectral index. In addition, the resolution of the VLA C configuration (>2.6″) is not sufficient to measure extended emission components with angular scales of an arcsecond that are best explained by shock ionization by a stellar wind. Shock ionization may be necessary to explain the extended nature of the λ=3.6 cm emission from Orion A-W (Tofani *et al.* 1995) and extended radio continuum emission reported for other maser sources such as IRAS 16293-2422 (Wootten 1989).

A plot of the radio continuum luminosity, $4\pi d^2 S_{6cm}$, versus bolometric luminosity for YSOs with water maser emission is shown in Fig. 6. In ionized wind models, the radio continuum luminosity is proportional to the wind mass loss rate (Panagia 1991). In most cases, the IRAS in-band luminosity is used to estimate the far-infrared luminosity which varies between about 1 and 120 $L_\odot$. As noted by Claussen *et al.* (1996), there is a linear relation between these two properties. With the addition of the new detections in this study, the correlation is even tighter. An unweighted linear least squares regression to the 15 known maser sources with radio emission gives the following relation and statistical error:

$$4\pi d^2(\mathrm{kpc}) S_{6cm}(\mathrm{mJy}) = L_{FIR}(L_\odot)/(32\pm3)$$

with a correlation coefficient of r=0.89. Two maser sources do not fit this relation: T Tauri, which is a complicated system with 2 or 3 components (Ray *et al.* 1997), and GSS30-IRS1, which despite its bolometric luminosity of 25 $L_\odot$, has no detectable λ=6 cm emission (Leous *et al.* 1991). SSV13 in NGC 1333 was also excluded from the fit since recent observations have revealed a second VLA source that could be responsible for the HH and H_2O emission (Rodriguez, Anglada, & Curiel 1997).

A similar relationship between radio luminosity and bolometric luminosity has been reported for a similarly selected sample of YSOs compiled by Rodriguez *et al.* (1989) and Cabrit & Bertout (1992), and for a higher luminosity sample of YSOs in the L1641 cloud (Morgan, Snell, & Strom 1990). The correlation between the radio continuum and far-infrared luminosity indicates that the radio luminosity is approximately a constant fraction of the bolometric luminosity for YSOs in this phase of evolution. This relationship suggests that a common mechanism generates the radio continuum flux in all of these objects. As noted by Cabrit & Bertout, a wind ionized by Balmer continuum photons can account for the level of the observed radio flux as a function of luminosity. However, this model requires that a Class 0/Class I source has the same fraction of Balmer continuum photons as a zero-age main sequence star of the same luminosity and a mechanism to populate the n=2 level of hydrogen.

5. Nature of the H_2O Maser Emission

Our VLA observations of Orion A-W, L1157, and L1251A (Figs. 1, 2, 5) have revealed three compact pairs of masers. The Orion A-W masers are clearly resolved with a projected separation of 46 AU while the L1157 and L1251A masers are unresolved at the 2σ level (<95 AU and <6 AU, respectively). All of the water masers are very near compact radio continuum sources: within 50 AU for Orion A-W, within 235 AU for L1157, and within 150 AU for L1251A. It appears that the masers lie in the circumstellar environments of their respective YSOs. In accordance with larger scale surveys (Wilking *et al.* 1994, Claussen *et al.* 1996), the maser features are all low in radial velocity relative to the ambient cloud (<10 km s^{-1}). Given the spatial resolution of these data and the positional uncertainties, we cannot determine whether the masers are aligned with larger scale outflows. However, if we assume the compact radio continuum source marks the position of the YSO, then we can investigate whether the radial velocities of the maser features indicate that they are gravitationally unbound. Unbound motions would be expected if the dense masing gas is carried by a stellar wind. The escape velocity from a solar mass object is given by:

$$\mathrm{v}_{esc}\ (\mathrm{km\ s^{-1}}) = 2.0(1''/\theta)^{0.5}(450\ \mathrm{pc}/d)^{0.5}$$

where θ is the angular separation from the YSO in arcseconds and d is the distance to the source in parsecs (Table 1). The projected angular separation observed between the maser and continuum source provides a lower limit to the true value of θ. If the radial velocity of the maser relative to the ambient cloud velocity exceeds v_{esc}, then the maser is gravitationally unbound. Relative radial velocities less than v_{esc} are inconclusive mainly because the relative radial velocity is a lower limit to the true relative space velocity. This could be large effect since many of the low-to-intermediate luminosity maser sources (such as L1157) have outflows which lie nearly in the plane of the sky (Wilking *et al.* 1994).

No gravitationally unbound masers can be identified from our data. Only the strongest Orion A-W maser has a resolved separation from the continuum source ($0.108\pm0.038''$). However, its relative radial velocity of 3.3 km s^{-1} is less than the escape velocity of 6 km s^{-1} at its projected distance from the continuum source. The highest velocity maser features in L1157 and L1251A could be gravitationally unbound if θ is greater than $0.25''$ and $0.1''$, respectively. Unfortunately, such separations are less than or equal to the positional uncertainties for these continuum sources. Future observations that simultaneously observe the maser and continuum source (such as for Orion A-W in this study) are critical for measuring accurately the small projected separations between masers and continuum sources. Also of great importance to investigations of the wind origin of the maser emission are multi-epoch studies that allow for estimates of the masers' tangential velocities.

6. Conclusions

We have conducted a continuum (λ=1.3, 3.6 cm, 6 cm, and 2.8 mm) and spectral line (H_2O and CO) study of five low-mass YSOs identified by the IRAS survey and with previously known H_2O maser activity. The major results are as follows:

1) For three of the five YSOs, we are able to constrain the location of the protostar

responsible for the known far-infrared emission by detecting thermal radio emission inside the IRAS error ellipse. Two thermal sources were found inside the L1251A IRAS ellipse, with one source coincident with H_2O masers.

2) In addition to thermal radio emission, millimeter continuum emission from cold dust was detected toward IRAS 20386+6751 (L1157). The high ratio of millimeter continuum luminosity to bolometric luminosity is characteristic of a Class 0 source.

3) Five VLA radio continuum sources (A-E) were observed toward IRAS 22343+7501, two of which correspond to near-infrared sources observed by Rosvick and Davidge (1995). Using this correspondence, we were able to register the absolute positions of the cluster members in the near-infrared image by Rosvick and Davidge (1995) and identify RD-D as the dominant luminosity source. One, and perhaps two, sources found outside of the IRAS error ellipse have thermal radio emission and are probably associated with less luminous YSOs in the cloud.

4) Radio emission associated with the IRAS sources has spectral indices between 0.19 and 1.15, consistent with a thermal ionized wind. The radio luminosity of the IRAS sources is nearly a constant fraction of the far-infrared luminosity, following a trend observed for more luminous YSOs. This relationship suggests a common radio emission mechanism for YSOs in this evolutionary phase.

5) Water masers mapped toward the IRAS positions in Orion A-W, L1157, and L1251A originate within the circumstellar environments of these YSOs, with projected separations within 50 AU, 235 AU, and 150 AU of their associated compact radio source. Due in part to the proximity of the masers and YSOs, no gravitationally unbound maser motions could be established.

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REFERENCES

André, P. 1995, Ap&SS, 224, 29

André, P., Ward-Thompson, D., & Barsony, M. 1993, ApJ, 406, 122

Bachiller, R., Liechti, S., Walmsley, C.M., & Colomer, F. 1995, A&A, 295, L51

Balázs, L.G., Eislöffel, J., Holl, A., Keleman, J., & Kun, M. 1992, A&A, 255, 281

Bally, J., Devine, D., & Alten, V. 1997, ApJ, in press

Cabrit, S. & Bertout, C. 1992, A&A, 261, 274

Ceccarelli, C., Hollenbach, D. J., & Tielens, A. G. G. M. 1996, ApJ, 471, 400.

Chandler, C.J. & Sargent, A.I. 1993, ApJ, 414, L29

Chernin, L. 1995, ApJ, 440, L97.

Claussen, M.J., Wilking, B.A., Benson, P.J., Wootten, A., Myers, P.C. & Terebey, S. 1996, ApJS, 106, 111

Comoretto, G., Palagi, F., Cesaroni, R., Felli, M., Bettarini, A., Catarzi, M., Curioni, G.P., Curioni, P., Di Franco, S., Giovanardi, C., Massi, M., Palla, F., Panella, D., Rossi, E., Speroni, N., & Tofani, G. 1990, A&AS, 84, 179

Curiel, S., Rodriguez, L.F., Bohigas, J., Roth, M., & Canto, J. 1989, Ap. Lett. Comm., 27, 299

Davis, C.J. & Eislöffel, J. 1995, A&A, 300, 851

Davis, C.J., Eislöffel, J., Ray, T.P., & Jenness, T. 1997a, A&A, in press

Davis, C.J., Ray, T.P., Eislöffel, J., & Corcoran, D. 1997b, A&A, in press

Elitzur, M. 1992, ARA&A, 30, 75.

Elitzur, M., Hollenbach, D. J., & McKee C. F. 1989, ApJ, 346, 983.

Felli, M., Palagi, F., & Tofani, G. 1992, A&A, 255, 293

Fiebig, D., Duschl, W.J., Menten, K.M., & Tscharnuter, W.M. 1996, A&A, 310, 199

Frank, A. & Mellema, G. 1996, ApJ, 472, 684

Fukui, Y. 1989, ESO Workshop on "Low Mass Star Formation and Pre-main Sequence Objects", ed. B. Reipurth, European Southern Observatory, Garching bei München, Germany, p. 95

Gueth, F., Guilloteau, S., & Bachiller, R. 1996, A&A, 307, 891

Gueth, F., Guilloteau, S., Dutrey, A., & Bachiller, R. 1997, A&A, in press

Hodapp, K.-W. 1994, ApJS, 94, 615

Kaufman, M.J. & Neufeld, D.A. 1996, ApJ, 456, 250

Kun, M. & Prusti, T. 1993 A&A, 272, 235

Lada, C. J. 1991, in The Physics of Star Formation and Early Stellar Evolution, eds. C.J. Lada & N.D. Kylafis, Kluwer Academic Publishers, Dordrecht, The Netherlands, p. 329

Ladd, E.F., Lada, E.A., & Myers, P.C. 1993, ApJ, 410, 168

Leous, J.A., Feigelson, E.D., André, P., & Montmerle, T. 1991, ApJ, 379, 683

Morgan, J.A., Snell, R.L., & Strom, K.M. 1990, ApJ, 362, 274

Mundy, L.G., Wilking, B.A., Blake, G.A., & Sargent, A.I. 1992, ApJ, 385, 306

Neufeld, D.A. & Hollenbach, D.J. 1996, ApJ, 471, L45

Panagia, N. 1991, in The Physics of Star Formation and Early Stellar Evolution, eds. C.J. Lada & N.D. Kylafis, Kluwer Academic Publishers, Dordrecht, The Netherlands, p. 565

Panagia, N. & Felli, M. 1975, A&A, 39, 1

Persi, P., Palagi. F., & Felli, M. 1994, A&A, 291, 577

Peter, W. & Eichler, D. 1996, ApJ, 466, 840

Plambeck, R. L., Wright, M. C. H., & Carlstrom, J. E. 1990 ApJ, 348, L65

Ray, T.P., Muxlow, T.W.B., Axon, D.J., Brown, A., Corcoran, D., Dyson, J., & Mundt, R. 1997, Nature, 385, 415

Reynolds, S.P. 1986, ApJ, 304, 713

Rodriguez, L.F., Anglada, G., & Curiel, S. 1997, ApJ, 480, L125

Rodriguez, L.F., Myers, P.C., Cruz-Gonzalez, I., & Terebey, S. 1989, ApJ, 347, 461

Rosvick, J.M. & Davidge, T.J. 1995, PASP, 107, 49

Sato, F. & Fukui, Y. 1989, ApJ, 343, 773

Schwartz, P.R., Frerking, M.A., & Smith, H.A. 1985, ApJ, 295, 89

Tafalla, M. & Bachiller, R. 1995, ApJ, 443, L37

Tapia, M., Persi, P., Bohigas, J,, & Ferrari-Toniolo, M. 1997, AJ, 113, 1769

Terebey, S., Vogel, S.N., & Myers, P.C. 1992, ApJ, 390, 181

Tofani, G., Felli, M., Taylor, G.B., & Hunter, T.R. 1995, A&AS, 112, 299

Torelles, J.M., Ho, P.T.P., Rodriguez, L.F., & Canto, J. 1985, ApJ, 288, 595

Tóth, L.V. & Walmsley, C.M. 1994, IBVS, 4107

Villuendas, E., Anglada, G., & Estalla, R. 1996, in Radio Emission from the Stars and the Sun, ASP Conference Series, Vol. 93, eds. A.R. Taylor & J.M Paredes,Astronomical Society of the Pacific, San Francisco, p. 56

Wilking, B.A. 1989, PASP, 101, 229

Wilking, B. A., Claussen, M. J., Benson, P. J., Myers, P. C., Terebey, S., & Wootten, H. A. 1994, ApJ, 431, L119.

Wootten, A. 1989, ApJ, 337, 858

Wootten, A., Wilking, B., & Claussen, M. 1998, in preparation

Wouterloot, J.G.A. & Brand, J. 1989, A&AS, 80, 149

Zhang, Q., Ho, P.T.P., Wright, M.C.H., & Wilner, D. J. 1995, ApJ, 451, L71

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Figure Captions

Fig. 1.— A plot of the Orion A-W region. The (0,0) position corresponds to the location of the source IRAS 05302-0537 given in Table 1. Only a portion of the IRAS error ellipse, which is 26″ x 5″ PA=87°, is shown. In addition to the IRAS source, we show the relative locations of our λ=1.3 cm source [cm(A)] and the two H_2O masers. The error bar representing the astrometric resolution of the cm source (0.04″x 0.03″) is shown; comparable error bars for the masers are not shown since they are smaller than the symbols marking their locations. The absolute positional uncertainty of the cm and maser source positions is $\pm0.1''$.

Fig. 2.— A plot of the L1157 region. The (0,0) position corresponds to the location of the source IRAS 20386+6751 given in Table 1. Only a portion of the IRAS error ellipse, which is 10″ x 5″ PA=12°, is shown. In addition to the IRAS source and error ellipse, we show the relative locations of our VLA λ=3.6 cm source [cm(A)], BIMA λ=2.8 continuum source [3mm Cont], and two VLA H_2O masers. Also displayed are an H_2 knot found by Davis and Eislöffel (1995) [H_2 (B1)] and the outflow axis as defined by the H_2 knots A1 and C1 (Davis and Eislöffel 1995).

Fig. 3.— The spectral energy distribution for L1157. Flux densities (and their one sigma uncertainties) are plotted from the IRAS Point Source Catalog (12, 25, 60, and 100 μm), IRAM λ = 1.3 mm observations by André (1997), our BIMA λ = 2.8 mm observations, and our radio continuum observations. The best fit to the data from 25 μm to 2.8 mm by a single temperature blackbody of 45 K is shown, yielding a $L_{BOL}\sim10\ L_\odot$. The distribution is characteristic of a Class 0 source.

Fig. 4.— A contour plot of the L1251A region taken from our VLA λ=3.6 cm observation, with the lowest contour at a level of two times the RMS noise (0.052 mJy beam^{-1}) and increasing in increments of 0.052 mJy beam^{-1}. The centroids of the λ=3.6 cm emission

peaks correspond to our point sources VLA A and B. We have used these positions to register the near-infrared map of Rosvick and Davidge (1995) with our VLA map, assuming their sources RD-D and RD-A correspond with our VLA sources A and B. The crosshairs represent the locations for five near-infrared sources observed by Rosvick and Davidge. VLA A (RD-D) is coincident with our VLA H_2O maser position.

Fig. 5.— A plot of the L1251A region. The (0,0) position corresponds to the location of the source IRAS 22343+7501 given in Table 1. In addition to the IRAS source and error ellipse, we show the relative locations of our VLA λ=3.6 cm sources A-D [cm(A) - cm(D)], VLA H_2O maser, and BIMA CO sources. The source cm(B) and cm(A) correspond to RD-A and RD-D, respectively.

Fig. 6.— A linear-linear plot of the radio luminosity in units of kpc^2-mJy vs. the IRAS in-band luminosity (7-135 μm) in $L_\odot$ for 15 YSOs with water maser emission. Data for sources not included in Table 1 were taken from data compiled in Table 3 of Claussen *et al.* (1996). The radio luminosity at λ=6 cm is used except for Haro 4-255FIR and L483, where the λ=3.6 cm flux density was used. For Orion A-W and IRAS 4B, the λ=6 cm flux density was extrapolated from shorter radio wavelength data. The solid line shows an unweighted linear least squares fit to the data. The one-sigma error bars shown assume a 10% error in the distance to the source and add this quadratically (with appropriate proportionality constants) to the uncertainties in the radio flux (y error) and IRAS flux densities (x error). A similar plot on a log-log scale, minus data for Orion A-W, L1157, and L1251A, has been presented in Fig. 23 of Claussen *et al.* (1996).