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DISTRIBUTION AND MOTION OF THE WATER MASERS NEAR IRAS 05413−0104

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ABSTRACT

We have used the NRAO Very Long Baseline Array to image water masers associated with the low-luminosity, young stellar object (YSO) IRAS 05413−0104 at four epochs over a period of 10 weeks. The maser images show the detail of a symmetric, jetlike structure about 300 mas in extent. The $23^\circ \pm 2^\circ$ position angle of the maser spot distribution is in excellent agreement with measured position angles for the observed larger scale H_2 and SiO emission distributions; radial velocities are in agreement with SiO measurements showing redshifted gas to the southwest and blueshifted gas to the northeast. We have detected proper motions of numerous maser spots averaging 30 ± 12 mas yr^{-1}, implying space velocities of 64 ± 27 km s^{-1} for a source distance of 450 pc. Some masers are located within a projected distance of 40 AU of the origin of expansion, the assumed position of the central source, suggesting that jet formation and acceleration takes place within this radius of the YSO. We compute an inclination of the outflow system to the plane of the sky of 4°, based on the relative magnitude of the proper motions and radial velocities of the masers. VLBI observations of water masers in YSOs are clearly demonstrated to be interesting and competitive probes of the kinematics of the gas in YSO jets.

Subject headings: ISM: jets and outflows — masers — shock waves — stars: mass loss — stars: pre–main-sequence

1. INTRODUCTION

Water maser emission is a good tracer of mass loss in young stars of all masses (see, e.g., Rodríguez et al. 1980 and Genzel & Downes 1977). This period of mass loss occurs during the so-called "embedded phase" of pre–main-sequence stars characterized by strong obscuration of the central star by large quantities of dust. Numerous water maser surveys of low-mass young stellar objects (YSOs) have shown that the masers are located close (<200 AU) to the central source, are highly variable on very short (<1 month) timescales, and are fairly common (see, e.g., Comoretto et al. 1990; Felli, Palagi, & Tofani 1992; Wilking et al. 1994; Xiang & Turner 1995; Meehan et al. 1998).

Masers are thought to arise through the shock excitation of ambient gas (see, e.g., Elitzur, Hollenbach, & McKee 1989). Although broad constraints on the temperatures and densities for water maser formation in shocked gas are well known (300–600 K, H_2 density $\approx 10^9$ cm^{-3}; Hollenbach 1997 and references therein), exact physical parameters are difficult to determine because of the nonlinear nature of maser emission. The masers exist in regions that are warmer and denser than the general physical conditions of the YSO environment. Their nonlinear nature provides episodes of extreme brightness temperatures that enable observations of the detailed gas kinematics with high-velocity resolution via radio spectroscopy. Detailed gas kinematics can be followed with multiepoch radio interferometric observations.

We present such multiepoch observations for which we successfully measure proper motions of water masers within 40–70 AU of the low-mass YSO IRAS 05413−0104 (hereafter IRAS 05413). This source is a young, cold, low-luminosity (14 $L_\odot$) source, lying at a distance of 450 pc in the L1630 cloud. Zinnecker et al. (1992) reported the measurement of a $\lambda = 1.1$ mm emission source and a spectral energy distribution that suggests a low-mass (0.4 $M_\odot$) central condensation. Marvel, Sargent, & McCaughrean (1998) have reported detection of this object at $\lambda = 3$ mm, along with a precisely measured position. The source lies at the center of a highly collimated CO outflow (W. R. F. Dent 1998, private communication). Molecular hydrogen emission reported by Zinnecker, McCaughrean, & Rayner (1998) defines a remarkably symmetric series of bow shocks, dubbed HH 212, which delineate a collimated jet 0.6 pc in extent. Unfortunately, near-infrared imaging has revealed nothing in the central region, presumably because of high obscuration.

The ratio of the millimeter-wave luminosity to the bolometric luminosity provides a measure of the YSO evolutionary status in the classification system of André, Ward-Thompson, & Barsony (1993). For IRAS 05413, this ratio is about 0.11, using its measured $\lambda = 1.1$ mm flux density of 200 mJy and a bolometric luminosity of 14 $L_\odot$ (Zinnecker et al. 1992). In the so-called class 0 sources, this ratio is greater than 0.2, thus placing IRAS 05413 on the borderline between a class 0 and class I source. A star in this evolutionary state is thought to be nearing the end of its main accretion phase. Monitoring shows that IRAS 05413 is a reliable source of maser emission whose spectrum had increased in complexity in 1994 with the addition of a blue component (Claussen et al. 1996); hence, it was selected for closer scrutiny.

2. OBSERVATIONS AND RESULTS

To refine the position and ascertain the activity level of the IRAS 05413 water masers, we observed the 6_{16}–5_{23} water maser transition at 22.235 GHz with the VLA on 1996 June 18 for approximately 40 minutes. We reduced the data in the standard way and created maps using the Astronomical Image Processing System (AIPS). We fitted two-dimensional Gaussian

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TABLE 1

IRAS 05413−0104 Properties

Property	Value	Reference
Position (B1950.0)	$5^{\rm h}41^{\rm m}18^{\rm s}.9$ (0.06), $-01°04'07''.9$ (1.1)	3.5 cm
	$5^{\rm h}41^{\rm m}18^{\rm s}.856$ (0.007), $-01°04'09''.22$ (0.1)	H_2O 1996 June mean of masers
	$5^{\rm h}41^{\rm m}18^{\rm s}.924$, $-01°04'09''.26$	H_2O 1994 May (red masers)
Distance (pc)	450	Genzel & Stutzki 1989
Flux (3.5 cm)	0.14 mJy	This Letter
Dust mass ($M_{\odot}$)	~0.4	Zinnecker et al. 1992
Bolometric luminosity ($L_{\odot}$)	14	Zinnecker et al. 1992
Bolometric temperature (K)	53	Zinnecker et al. 1992
Position angle of maser components (deg)	23 ± 2	This Letter
Mean expansion velocity of maser components (km s^{-1})	64 ± 27	This Letter
Outflow Inclination (deg)	4^{+3}_{-1}	This Letter

components to the strong, unresolved maser emission in a number of channels and measured the mean position obtained. The array was in the DnC configuration. The accuracy of the measured absolute position, given in Table 1, is about $0''.1$, limited by the uncertainty in the reference frame of the phase calibrator.

IRAS 05413 was observed with the 10 stations of the Very Long Baseline Array (VLBA) and a single antenna from the Very Large Array (VLA), both facilities of the National Radio Astronomy Observatory, on 1996 July 4, July 26, August 16, and September 15. Approximately 4 hr per epoch were devoted to observations of IRAS 05413. Observations of strong continuum sources were made for calibration purposes and approximately 4 hr were spent observing IRAS 05338−0624. Only a single maser spot was detected toward IRAS 05338−0624, and it will not be discussed further here.

The VLBA data were recorded with a 4 MHz bandwidth centered at a velocity of 3.5 km s^{-1} relative to the local standard of rest (LSR). Both right and left circular polarizations were recorded with 1 bit sampling and correlated with the NRAO VLBA correlator in order to provide 256 spectral channels for each polarization averaged every 3.2 s. This correlator mode provided a velocity resolution of 0.21 km s^{-1} channel^{-1}. Data reduction was performed using the standard software contained in the AIPS package. Delays were measured via observations of strong continuum sources and calculated by performing fringe-fitting. Residual fringe rates were determined by fringe-fitting on a single, strong spectral channel and then removed. Amplitude calibration was accomplished by fitting the bandpass-corrected, total-power, on-source spectra of each antenna in the array to a template total-power, on-source spectrum observed with a sensitive antenna at a high-elevation angle. The absolute amplitude calibration is accurate to about 20%.

The channel with the greatest flux on most baselines was used in an iterative self-calibration mapping procedure. The self-calibration solutions determined were then applied to the second strongest channel (approximately 20 channels blueward of the self-calibration channel), and a map was made. The rms noise (≈15 mJy beam^{-1} for all four epochs) in this map was near the expected theoretical noise limit, and the source structure was consistent with good self-calibration solutions. We then applied the self-calibration solutions to all channels and made a highly tapered map to search for sources of maser emission.

Naturally weighted maps for each velocity channel were produced using the AIPS task IMAGR. Because of the large separation of some groups of components, multiple fields were imaged simultaneously, using a cell size of 86 μas. The resultant synthesized beam was 1.2 × 0.5 mas, approximately 0.54 × 0.23 AU at the distance of IRAS 05413. To parameterize each maser feature, two-dimensional Gaussians were fitted to any component appearing in adjacent spectral channels with a flux in excess of $8\sigma_{\rm rms}$. Components with fluxes above the 8 σ limit that occur in two or more spectral channels were averaged in position and velocity using a flux-squared–weighting scheme.

The VLA observed the IRAS 05413 region in the 8.46 GHz continuum on 1997 October 5 and again on October 29. The array was in the D configuration. Both the AC and the BD IF pair were employed with 50 MHz bandwidths. Observations of 3C 48 set the flux scale (assumed flux density $S_{8.46} =$ 3.24 Jy), and 0541−056 (measured flux density $S_{8.46} = 0.75$ Jy) served as phase calibrator. The resolution of the naturally weighted images was $11''.5 \times 9''.3$ and reached a sensitivity of 13 μJy beam^{-1}. This beam provided a positional uncertainty of about $0''.17$ for a point source with a signal-to-noise ratio of 30.

Six sources were clearly detected in the image. One source, at the edge of the field, is also seen in the NRAO VLA Sky Survey (Condon et al. 1998), and it is assumed to be extragalactic. The second brightest source lies nearly coincident with the position of water maser emission from IRAS 05413 and is probably emission associated with the protostar or its jet. Its position is given in Table 1, along with its flux density.

3. ANALYSIS

A map of the maser spots, a maser spectrum, and a proper-motion plot are shown in Figure 1. The distribution of maser spots forms a pattern that is clearly visible in each epoch. The ambient cloud velocity is 1.6 km s^{-1}. Generally, three to six blueshifted (−4.0 to −0.0 km s^{-1}) masers lie to the northeast of 14–34 redshifted masers on scales of about 100 mas at a position angle of 23° ± 2°. This position angle agrees quite well with larger scale measurements of the outflow traced by SiO (23° ± 2°; Marvel et al. 1998) and H_2 emission (24°; Zinnecker et al. 1998). The maser ensembles on each side of the YSO also show some alignment along the axis of the flow. At least three northeastern blueshifted masers are spread along a similar position angle from epoch to epoch, gradually separating over the course of the observations from a span of 2 AU at the beginning to 4.5 AU at the end, in projected distance. The numerous redshifted masers form a "fishhook" structure that emulates bow shock structures seen on much larger (to 4′) scales in H_2 emission. This structure has a velocity range from 0.0 to 3.5 km s^{-1}. The higher velocity masers (3.5–5.0 km s^{-1}) lie at the southeastern extreme "hook," while more moderate-velocity masers congregate along the "shaft" and elsewhere. The red features encompass the axis of the flow, suggesting an opening angle certainly less than (and probably

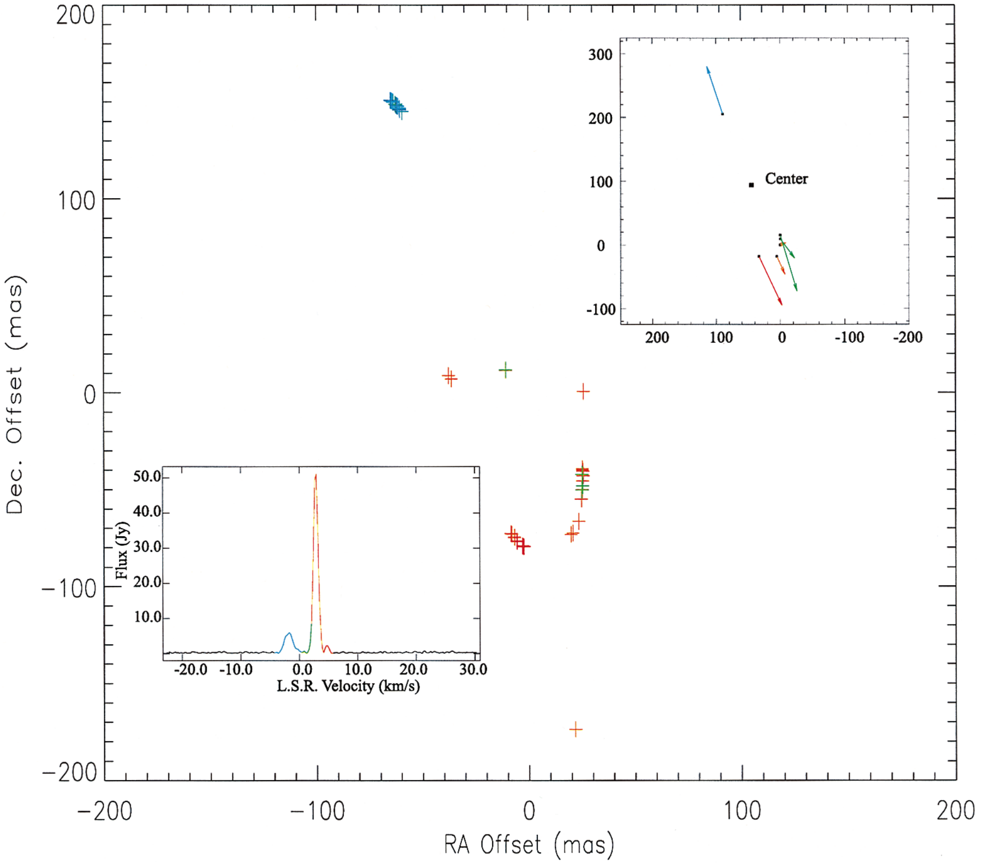

FIG. 1.—The locations of the maser spots detected in epoch I. The spots have been color coded according to their velocity. Blue spots lie in the velocity range −4.0–0.0 km s^{-1}, green spots lie in the velocity range 0.0–1.5 km s^{-1}, orange spots lie in the velocity range 1.5–3.5 km s^{-1}, and red spots lie in the velocity range 3.5–5.0 km s^{-1}. The inset spectrum illustrates the color coding and is a spectrum produced from the shortest VLBA baseline near transit. The inset in the top right-hand corner of the figure illustrates the proper-motion vectors derived from spots detected in both epoch I and epoch II. The color coding matches that of the main figure and the spectral inset. The size of the vector in units of milliarcseconds is the magnitude of the proper motion in units of km s^{-1} for the assumed source distance of 450 pc.

much less than) 42° ± 10° for the flow, and the masers occur along the flow, perhaps in a sheath of entrained material.

The 1996 June maser data resolved the red and blue components of the masers, which lie at a position angle of 19° ± 8° at a separation of 200 mas, in excellent agreement with the position angle and mean separation of blue and red components in the VLBA data taken the following month. Our absolute VLA measurement of the mean maser position (Table 1) agrees well with those of both centimeter and millimeter point sources. We believe that this mean position is the best estimator of the position of the star. Two pieces of evidence convince us that the masers are associated closely (within 40–70 AU) with the outflow centered on the YSO. First, the striking linear distribution of the masers matches precisely the position angle of the larger scale outflows probed by molecular emission. Second, the blueshifted masers lie the farthest north and the redshifted masers lie farthest to the south, which matches the velocity distribution of the large-scale molecular outflow.

The position measurement across epochs in VLBI data is complicated by the fact that the self-calibration step necessary for imaging causes a loss of absolute position information for each epoch. A careful examination of the water maser spot distributions for each of our epochs demonstrates that no simple translation of positions can bring the images for each epoch into registration; the patterns also clearly expand along the axis of the flow. However, the clear epoch-to-epoch patterns observed in this source suggest unambiguous identification of various maser features across the approximately 4 week period between epochs. This characteristic allows us to measure the proper motions of the masers and to probe directly the kinematics of material involved with the flow.

It is important to note that although the spectrum is rather simple, with three or four distinct peaks detected in each epoch, the spatial distribution is far more complicated. The maximum number of maser spots we detected was in epoch IV (40), while the least detected was in epoch III (17). The spectra for these two epochs are not significantly different qualitatively, but the flux of the spectral peaks was different by a factor of 2 or more. This result clearly indicates that studies of these sources using only single-antenna observations are inadequate for resolving the complex nature of the maser distribution.

If the motions of the masers represent the motion of real physical objects, such as “bullets,” they left a common origin about 3 years before our observations. This timescale coincides with that for the lifetime of the blueshifted feature seen in single-antenna–monitoring data, which arose between 1994 July 23 and September 30 (Claussen et al. 1996). The spatial distribution seen in a VLBA observation from 1994 October 1 (L. Greenhill 1997, private communication) shows a pattern similar in detail to those observed nearly 2 years later. This suggests that the masers do not represent bullets traveling through the cloud but are more likely dense shock fronts propagating into the sheath of molecular material that enshrouds the jet. Thirty-six pairs of the 102 individual masers measured can be identified reliably in more than one epoch, demonstrating that the majority of the masers originate in coherent structures propagating into ambient material. The fact that molecular material is still found in this region also suggests that the jet has a small opening angle, since otherwise the jet could have cleared the region of ambient gas.

During the time period covered by our images, many masers show a continuous identity not only in position but also in velocity and strength. The expansion observed in the overall map results from the common motions of the masers that constitute it; some distortion results from the peculiar motions of the individual features. A detailed discussion of the proper motions of the dozens of masers observed is beyond the scope of this Letter and will appear elsewhere. Here we report the general result that the masers clearly show expansion from a common origin across all epochs, at an average spatial velocity (assuming an inclination of 5°) of 64 ± 27 km s^{-1}. Comparison of the radial velocity and proper motion of maser spots suggests that the outflow in IRAS 05413 lies with the northern axis inclined toward the Earth at an inclination 4^{+3}_{-1} deg to the plane of the sky.

A number of papers, including Litvak (1969), Elitzur et al. 1989, and Kaufman & Neufeld 1996 (see Hollenbach 1997 and references therein), propose models of maser emission in shocks produced by the interaction of mass loss and ambient material. The average space velocities of the masers suggest that they arise in J-type shocks, which move faster than about 40 km s^{-1}. Shocks that propagate close to the plane of the sky provide ample coherence lengths for maser amplification. The fishhook structure we observe bears a strong resemblance to a bow shock and is a natural consequence of a collection of shocks driven by the YSO jet into surrounding molecular material. In this picture, the necessity to achieve a sufficient path length in the masing lines results in the masers displaying the bow shock pattern in cross section in the plane of the sky. These water maser structures are reminiscent of the knots and shock structures of the HH 30 ionized jet observed with the *Hubble Space Telescope* (*HST*) (Burrows et al. 1996) or the HH 34 study made by Eisloffel & Mundt (1992). Both our study of IRAS 05413 and the study of HH 30 trace the outflow very close to the powering YSO. Both studies measure similar proper motions, but our observations of the water masers in IRAS 05413 probe a much higher extinction region in a source 3 times farther away than HH 30 and measure proper motions in only 1 month compared with 1 yr for the *HST* data, or 4 yr for HH 34. Thus, it is clear that multiepoch VLBI observations of water masers are a most valuable probe of the kinematics of the jets emanating from embedded YSOs.

4. CONCLUSIONS

We have mapped the water maser distribution near IRAS 05413 in four epochs extending over about 10 weeks. We find that the masers lie in an elongated outflowing distribution, which is aligned within only a few degrees of the large-scale H_2 emission structure (HH 212) centered on this source. This is clear evidence that the water masers trace the same outflow that is responsible for the H_2 jet emission, but on a much smaller physical scale. The masers exhibit proper motions consistent with an association with an outflow jet accelerated to a velocity of 64 km s^{-1} within 40–70 AU of the central source. These observations suggest that jet formation, acceleration, and collimation occur within this radius.

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