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LETTER

Letter to the Editor

Cross-calibrated VLA observations of H_2O maser and 1.3 cm continuum emission in IRAS 18162−2048 (= HH 80-81 IRS)

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Abstract. We report simultaneous continuum (1.3 cm) and H_2O maser line observations, made with the Very Large Array (A configuration), toward IRAS 18162−2048, the luminous exciting source of the HH 80–81 complex. The continuum observations, cross-calibrated with the H_2O maser emission, provide information of the thermal jet of this young massive star with unprecedented angular resolution and fidelity. We find that the jet is already collimated on scales smaller than 100 AU. The analysis of the new 1.3 cm data and of previously obtained 3.6 cm data show that the source has the frequency dependences in major axis and flux density that characterize biconical jets. In particular, we find $\theta_{\rm maj} \propto \nu^{-0.7\pm0.1}$ and $S_\nu \propto \nu^{0.8\pm0.1}$. An improved determination of the mass loss rate in ionized gas, $\dot{M}_{\rm ion} \simeq 9 \times 10^{-7} M_\odot$ yr^{-1}, is provided with these new observations.

As it was known from previous studies, the H_2O maser emission does not coincide with the thermal jet but with a faint source of radio continuum emission displaced by $\sim7''$ to the northeast of the thermal jet. The H_2O masers appear in two compact clusters separated by ∼20 mas. One of the clusters is formed by spots in a linear geometry. The kinematics of these maser spots and their large blueshift with respect to the radial velocity of the parental molecular cloud suggest that they trace material accelerated by outflow phenomena, instead of a possible disk.

Key words: stars: individual: IRAS 18162−2048 – stars: individual: HH 80-81 IRS – stars: formation – ISM: Herbig-Haro objects – ISM: jets and outflows

1. Introduction

The HH 80–81/GGD 27 region in Sagittarius has been the subject of numerous studies because it constitutes one of the few cases of collimated outflows powered by a young massive star. The driving source, IRAS 18162−2048, has a bolometric luminosity of ∼20,000 $L_\odot$ and a large molecular outflow emanates from this source (Yamashita et al. 1989). The region has been studied in the infrared, revealing a small cluster of sources, among others by Aspin et al. (1991, 1994), Aspin & Geballe (1992), Aspin (1994) and Stecklum et al. (1997). The two Herbig-Haro objects 80 and 81 are among the brightest known (Reipurth & Graham 1988; Heathcote, Reipurth, & Raga 1998), and in Hα they are intrinsically 20 times more luminous than the classic object HH 1 (Girart et al. 1994).

In an early work, Rodríguez & Reipurth (1989) detected both HH objects in the radio continuum and noted that the radio counterpart to the IRAS source is elongated toward the HH objects. In a detailed high angular resolution study at 6 cm and 3.6 cm, Martí, Rodríguez & Reipurth (1993) found a highly collimated bipolar thermal radio jet to emanate from the source. On the opposite side of the IRAS source with respect to HH 80–81 and along the flow axis they found a resolved object, called HH 80-North, which is almost certainly an obscured counterpart to the optically visible HH objects; the total projected extent of the flow is thus about 5.3 pc, at a distance of 1.7 kpc. The Herbig-Haro nature of HH 80-North has been recently supported by the detection of associated molecular gas of anomalous excitation (Girart et al. 1994; Girart, Estalella & Ho 1998). In subsequent studies, Martí, Rodríguez & Reipurth (1995; 1998) measured large proper motions in the thermal jet and detected the appearance and proper motions of a new pair of knots, located symmetrically with respect to the source.

There is also a relatively bright (reaching flux densities of tens of Jy) H_2O maser in the region (Rodríguez et al. 1980). The VLA measurements of Gómez et al. (1995) show that it does not coincide with the thermal jet, but with a very faint radio continuum source located at $\sim7''$ to the northeast of the thermal jet. Clearly, the IRAS 18162−2048 region contains a young cluster of stars, the most luminous of which is believed to be associated with the thermal jet.

In this paper we report simultaneous Very Large Array (VLA) observations of the 1.3 cm continuum and H_2O maser

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emission toward the thermal radio jet in the IRAS 18162−2048 region. The main purpose of this work was to study both emissions with an angular resolution of 0.″1 (170 AU).

2. Observations and data reduction

The 1.3 cm continuum and H_2O maser ($6_{16}\rightarrow5_{23}$; ν = 22235.080 MHz) observations were made with the VLA of the National Radio Astronomy Observatory (NRAO)[1] in the A configuration on 1998 May 14 and 21. We observed simultaneously two different bandwidths of 25 MHz (7 channels of 3.125 MHz each) and 3.125 MHz (63 channels of 48.8 kHz each), respectively. Both the right and left circular polarizations were sampled in the two different bandwidths. The broad bandwidth was centered at the frequency of 22285.080 MHz for continuum measurements, while the narrow bandwidth was centered at the frequency of the H_2O $6_{16}\rightarrow5_{23}$ maser line (22235.080 MHz) with $V_{\rm LSR}$ = –69.0 km s^{-1}. The absolute amplitude calibrator was 1331+305 and the phase calibrator was 1733–130, both names in the J2000 coordinate system. The bootstrapped flux densities of 1733–130 were found to be 3.71±0.06 and 3.79±0.08 Jy, for 1998 May 14 and 21, respectively. Once the strongest H_2O maser component was identified in a particular spectral channel of the narrow bandwidth (the channel at $V_{\rm LSR}$ = –61.1 km s^{-1}), we self-calibrated its signal in phase and amplitude. The self-calibration procedure on the first day was initiated with a point source model, whose position was that of the strongest maser component. To measure it, we used the AIPS task MAXFIT on the corresponding channel map externally calibrated with 1331+305 and 1733–130. The phase and amplitude corrections finally obtained were then applied (as cross-calibration) to both the narrow and broad bandwidth data. To better align the positions of both days of observation, we used another cross-calibration procedure for the second day, i.e, taking the self-calibration phase solution of the 1998 May 14 as the first self-calibration model for 1998 May 21. For more details of the system parameters and calibration procedures see Torrelles et al. (1996).

In order to study the continuum emission with maximum sensitivity, we produced a map with the task IMAGR of AIPS and the "robustness" parameter set to 5 (Briggs 1995), equivalent to natural weighting. The resulting angular resolution was ∼0.″1 and the map is shown in Fig. 1.

With regard to the H_2O maser emission, individual spectral channel maps (63 channels of 0.66 km s^{-1} each) were produced with the same weighting of the *(u,v)* data as for the continuum. The spectrum observed in 1998 May 14 is shown in Fig. 2. The uncertainty in the relative positions between the masers spots is dominated by the noise statistics and can be estimated (e.g., Meehan et al. 1998) to be σ = (beam size)/(2×signal-to-noise ratio). These relative uncertainties turn out to be in the range of a few mas. In Fig. 3 we show the relative positions of the water masers spots for 1998 May 14.

[1] The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

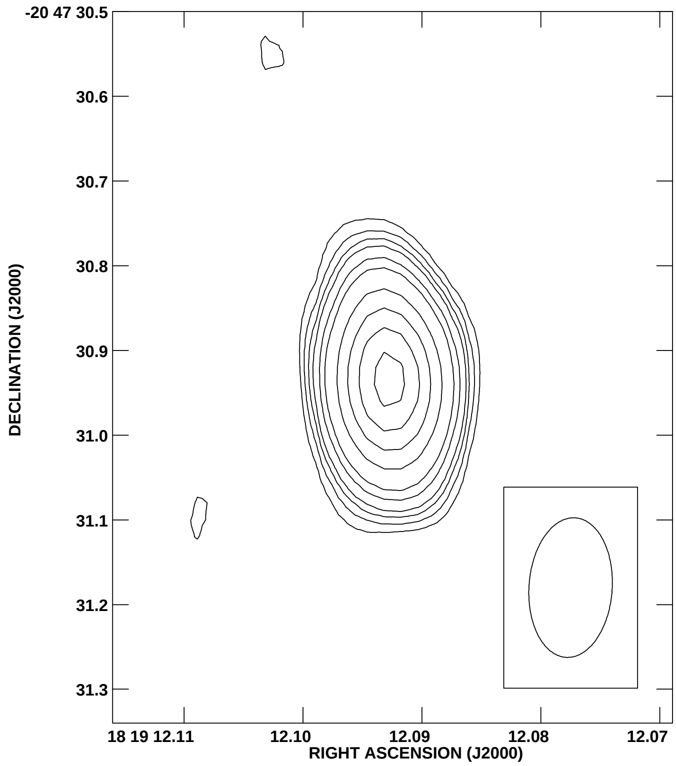

Fig. 1. 1.3 cm continuum contour map of the thermal jet in IRAS 18162−2042. Levels are −3, 3, 4, 5, 6, 8, 10, 15, 20, 25, and 30 times 0.11 mJy beam^{-1}, the rms noise of the map. The half power contour of the beam (0.″17 × 0.″10; PA = −4°) is shown in the bottom right corner.

On the other hand the accuracy of the absolute positions of both continuum and masers depends on the accuracy of the position of the phase calibrator, and is estimated to be ∼ 0.″05.

3. Results

3.1. 1.3 cm continuum jet source

The contour map of the 1.3 cm continuum emission (Fig. 1) shows an elongated source centered at $\alpha(2000) = 18^h19^m12.^s093$; $\delta(2000) = -20°47'30.''94$ and with a total flux density of 5.1±0.2 mJy. A Gaussian ellipsoid least-squares fit to the source gives deconvolved half-power widths of $0.''12\pm0.''01\times0.''05\pm0.''01$ and PA = 17° ±3°. A direct, Gaussian ellipsoid fit to the *(u,v)* data using the task UVFIT of AIPS gives true half-power widths of $0.''13\pm0.''01\times0.''05\pm0.''01$ and PA = 17° ±4°, in excellent agreement with the deconvolved values obtained from the fit made to the image. This fit also gives a total flux density of 4.8±0.2 mJy.

The observed minor axis suggests that collimation is present on a radius comparable or smaller than about 40 AU. To be certain that we are observing the core of this radio jet, a comparison with observations made at other frequencies is helpful, in particular to search for the frequency dependences in major axis and flux density that have been observed in other sources (e.g. Anglada 1996). For this purpose, we reanalyzed the VLA-A,

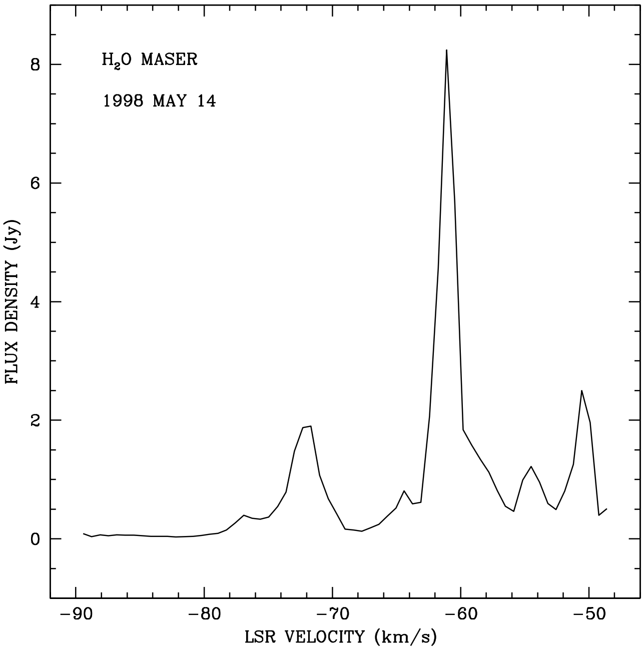

Fig. 2. Spectrum of the H_2O maser emission on 1998 May 14.

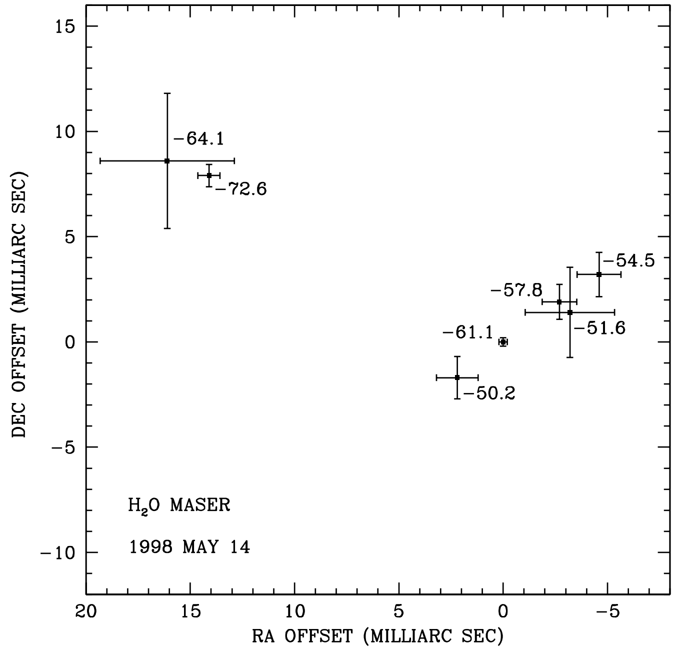

Fig. 3. Map showing the positions of the H_2O masers (crosses) in the region with respect to the brightest spot in 1998 May 14 (with $V_{\rm LSR} = -61.1\,{\rm km\,s^{-1}}$). The position of this reference spot is $\alpha(2000) = 18^h19^m12\overset{s}{.}509$; $\delta(2000) = -20°47'27\overset{''}{.}42$, as measured with the AIPS task MAXFIT. The $V_{\rm LSR}$ of each spot is shown next to it. The size of the crosses reflects the uncertainty in the relative positions between maser spots, estimated as the beam size over twice the signal-to-noise ratio (see text).

3.6-cm data taken in 1990 and discussed in Martí et al. (1993). In contrast to the 1.3-cm data (see Fig. 1) that shows a single, well-defined component, the 3.6-cm data (see Fig. 5 of Martí et al. 1993) shows a core component with fainter condensations at both sides. These condensations are known to exhibit large proper motions (Martí et al. 1995). To obtain a measurement of the parameters of this core at 3.6-cm, we did fits to the *(u,v)* data using the task UVFIT and restricting the fit to spacings longer than 300 kλ. This restriction minimizes the contribution from structures larger than about $0\overset{''}{.}7$. We did fits varying the size of this inner "hole" and obtained robust results, consistent with half-power widths of $0\overset{''}{.}26 \pm 0\overset{''}{.}02 \times 0\overset{''}{.}05 \pm 0\overset{''}{.}01$ and PA = $23° \pm 2°$, and a total flux density of 2.2±0.1 mJy. We then obtain dependences of $S_\nu \propto \nu^{0.8\pm0.1}$ and $\theta_{\rm maj} \propto \nu^{-0.7\pm0.1}$, for the flux density and angular size of the major axis. These dependences are in good agreement with those expected for a jet with constant opening angle, terminal velocity, ionization fraction, and electron temperature, that are expected to be $S_\nu \propto \nu^{0.6}$ and $\theta_{\rm maj} \propto \nu^{-0.7}$ (Reynolds 1986). The angular size of the minor axis is determined with low statistical significance and it is difficult to search for a frequency dependence in it. The opening angle can be estimated to be $\theta_0 = 2\,\tan^{-1}(\theta_{\rm min}/\theta_{\rm maj})$, where $\theta_{\rm min}$ and $\theta_{\rm maj}$ are the minor and major axes of the jet. From the available data, we find $\theta_0 \simeq 30° \pm 10°$. Assuming a fully ionized plasma with an electron temperature of 10^4 K, and a terminal velocity of 500 km s^{-1} (the average velocity in the sky of the knots studied by Martí et al. 1995, 1998), we find, following the formulation of Reynolds (1986), that the mass loss rate in ionized gas in the jet is $\dot{M}_{\rm ion} \simeq 9 \times 10^{-7} M_\odot$ yr^{-1}. This mass loss rate in ionized gas is very similar to that found for Cep A HW2 (Rodríguez et al. 1994), another thermal jet powered by a massive star. We also find that the mass loss rate in ionized gas implies a momentum rate of $\dot{P}_{\rm ion} \simeq 5 \times 10^{-4} M_\odot$ yr^{-1} km s^{-1} and a mechanical energy of $L_{\rm mech} \simeq 20\ L_\odot$. The momentum rate in the large scale flow, as derived by Yamashita et al. (1989) from their CO observations is $\dot{P}_{\rm CO} \simeq 5 \times 10^{-2} M_\odot$ yr^{-1}. Despite the uncertainties in both determinations of the momentum rate, $\dot{P}_{\rm CO} \gg \dot{P}_{\rm ion}$. This discrepancy is found systematically in this type of studies. It is attributed either to the possibility that the ionized flow underestimates the real, mostly neutral flow or to the fact that the large-scale flow traced by CO reflects the past outflow activity of the source that could have been much stronger.

3.2. H_2O masers

The position of the brightest velocity component (with $V_{\rm LSR}$ = –61.1 km s^{-1}) is $\alpha(2000) = 18^h19^m12\overset{s}{.}509$; $\delta(2000) = -20°47'27\overset{''}{.}42$. As found by Gómez et al. (1995) and confirmed by us, the maser emission does not coincide with the thermal jet, but is displaced by $\sim 7''$ to its northeast. Gómez et al. (1995) detected a very faint radio continuum source coincident with the maser spots. This source is not detected by us at 1.3 cm with the 3σ continuum upper limit being 0.3 mJy. One of the 2.6-mm continuum peaks found by Yamashita et al. (1991), called CS 3, could also be the same object as the H_2O/centimeter source. We detect a total of 7 H_2O maser spots in the region, corresponding to the radial velocities shown in Fig. 3. These spots are distributed in two clusters separated by about 20 mas. Five of the spots appear aligned in a linear distribution (see Fig. 3), reminiscent of the morphology expected for H_2O masers in a disk seen edge-on. There are, however, two strong arguments that seem to rule out this possibility. First, the velocity distribution of the spots does not show the systematic gradient expected for a disk (see, for example, Torrelles et al. 1998). Second, as it is well known since its detection (Rodríguez et al. 1978, 1980), the LSR velocity range of this maser (the strongest features are typically between -80 and $-50\,\mathrm{km\,s^{-1}}$) is strongly blueshifted with respect to the LSR velocity of the cloud, $+10\,\mathrm{km\,s^{-1}}$. If the maser emission were arising from a circumstellar disk, one would expect its average velocity to be close to that of the ambient molecular cloud. Most likely, the H_2O masers in this region originate from accelerated material, possibly by shocks produced by outflow phenomena. It has recently become evident that H_2O masers in a well collimated outflow can also produce linear distributions (Torrelles et al. 1997; Claussen et al. 1998). However, the lack of a systematic velocity gradient and of a known redshifted component seems to argue against this interpretation. Although associated with outflowing gas, the precise nature of this H_2O maser remains uncertain.

4. Conclusions

Using the VLA in its A configuration we have studied the 1.3 cm continuum and H_2O maser emissions toward IRAS 18162−2048, the exciting source of the HH 80–81 system. We obtained an image of the core of the thermal jet with unprecedented angular resolution and fidelity. The jet is collimated on scales smaller than ∼100 AU. Comparison with previously obtained 3.6 cm observations shows that the source has frequency dependences in major axis and flux density of $\theta_{\rm maj} \propto \nu^{-0.7\pm0.1}$ and $S_\nu \propto \nu^{0.8\pm0.1}$, consistent with those that theory predicts for simple biconical thermal jets. A mass loss rate in ionized gas of $\dot{M}_{\rm ion} \simeq 9\times10^{-7} M_\odot$ yr^{-1} is derived from these new observations.

The maser emission is localized in two clusters about $\sim7''$ to the northeast of the thermal jet. The clusters are separated by 20 mas and one of them shows the linear geometry. The large blueshift of the masers with respect to the radial velocity of the ambient molecular cloud suggests that they could be originated in material accelerated by outflow phenomena.

Cross-calibrated observations of the type presented here appear as a most promising tool to reliably study time variations in the evolution of thermal jets, that could include ejection of condensations, changes in orientation of major axis or source morphology, and variations in mass loss rate. These future observations are expected to provide important clues towards the understanding of the mechanisms that accelerate and collimate jets in young stars.

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