MULTIPLE SOURCES TOWARD THE HIGH-MASS YOUNG STAR S140 IRS 1

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ABSTRACT

S140 IRS 1 is a remarkable source where the radio source at the center of the main bipolar molecular outflow in the region is elongated perpendicular to the axis of the outflow, an orientation opposite to that expected if the radio source is a thermal jet exciting the outflow. We present results of 1.3 cm continuum and H2O maser emission observations made with the Very Large Array in its A configuration toward this region. In addition, we also present results of continuum observations at 7 mm and reanalyze observations at 2, 3.5, and 6 cm (previously published). IRS 1A is detected at all wavelengths, showing an elongated structure. Three water maser spots are detected along the major axis of the radio source IRS 1A. We have also detected a new continuum source at 3.5 cm (IRS 1C) located ≥0.60° northeast of IRS 1A. The presence of these two young stellar objects (IRS 1A and 1C) could explain the existence of the two bipolar molecular outflows observed in the region. In addition, we have also detected three continuum clumps (IRS 1B, 1D, and 1E) located along the major axis of IRS 1A. We discuss two possible models to explain the nature of IRS 1A: a thermal jet and an equatorial wind.

Key words: ISM: individual (S140 IRS 1) — ISM: jets and outflows — masers — stars: formation — stars: pre-main-sequence

1. INTRODUCTION

The process of low-mass star formation is reasonably well understood. The accepted model (e.g., Shu et al. 1987) requires a disk–young stellar object (YSO) outflow system, and it has been supported by theoretical and observational results (e.g., Evans 1999 and references therein). In addition, bipolar molecular outflows associated with low-mass stars are believed to be driven by their jets, which can be observed at subarcsecond scales, and this constitutes the best evidence of collimation at the smallest scales now known (e.g., Anglada 1996). However, the process of high-mass star formation is not well understood yet. In fact, although molecular outflows seem to be common also among high-mass stars (Gómez et al. 1999; Zhang et al. 2001; Ridge & Moore 2001; Beuther et al. 2002; Shepherd 2005), there is still a deficit in the detection of circumstellar disks and jets associated with massive YSOs (e.g., Cepheus A HW2: Rodríguez et al. 1994; Patel et al. 2005; Curiel et al. 2006; IRAS 12026+4104: Cesaroni et al. 1999; Trinidad et al. 2005; Sridharan et al. 2005; AFGL 490: Schreyer 2005; Curiel et al. 2006; IRAS 20126+4104: Cesaroni et al. 1999; Trinidad et al. 2003). In addition, water maser emission has also been detected toward other young stellar objects (IRS 1A and 1C) could explain the existence of the two bipolar molecular outflows in the region (Preibisch & Smith 2002; Weigelt et al. 2002), one of them with an orientation similar to the CO outflow (160°/340°) and the other one in the 20°/200° direction. Both bipolar outflows seem to be centered on IRS 1. The region S140 IRS has also been studied in the infrared and optical bands (Eiroa et al. 1993), NH3 lines (Verdes-Montenegro et al. 1989), and radio-continuum emission (Schwartz 1989; Evans et al. 1989). More recently, Hoare (2006) has observed IRS 1 at 6 cm during three epochs with MERLIN; he showed through a very detailed analysis that it is highly elongated in the northeast-southwest direction, and he proposed that the radio continuum traces an ionized equatorial wind, driven by radiation pressure from the central star and oriented in the northeast-southwest direction, perpendicular to the CO bipolar outflow. In addition, water maser emission has also been detected toward the S140 IRS region (e.g., Tofani et al. 1995; Lekht et al. 1993; Lekht & Sorochenko 2001; Trinidad et al. 2003).

In this paper we report and discuss new high angular resolution observations of 1.3 cm continuum and water maser emission toward the S140 IRS region carried out with the Very Large Array (VLA) in the A configuration. In order to present a full study of IRS 1, we have also analyzed 7 mm continuum observations (from the VLA data archive; see also Gibb & Hoare 2007) and reanalyzed VLA centimeter continuum observations (previously published by Schwartz 1989 and Tofani et al. 1995). We describe the observations in § 2 and present the results in § 3. In § 4 we discuss the nature of the multiple continuum sources that we detect in the region, while our main conclusions are summarized in § 5.

2. OBSERVATIONS

The observations toward the S140 IRS region were made with the VLA of the National Radio Astronomy Observatory.
We observed simultaneously 1.3 cm continuum and water maser emission. We used two different bandwidths, one of 25 MHz with seven channels for the continuum and another one of 3.125 MHz with 63 channels for the maser line emission. Both the right and left circular polarizations were sampled in the above two different bandwidths, which were averaged in order to improve the sensitivity. The broad bandwidth for the continuum observations was centered at 22285.080 MHz, while the narrow bandwidth for the line observations was centered at the frequency of the H$_2$O $6_{16} \rightarrow 5_{23}$ maser line (rest frequency 22235.080 MHz) with $V_{\text{LSR}} = -9.0 \text{ km s}^{-1}$ in velocity. The absolute amplitude calibrator was 3C 286, with an adopted flux density of 2.51 Jy, while the phase calibrator was B2021+614, with a bootstrapped flux density of 2.14 ± 0.05 Jy. The water maser line and continuum data were reduced and calibrated using the standard techniques using the NRAO AIPS software package. After the first calibration, we searched the narrow-bandwidth data for the spectral channel with the strongest water maser emission, and then its signal was self-calibrated in phase and amplitude. We then cross-calibrated the data, applying the phase and amplitude corrections to both the narrow and the broad bandwidths. In this way, the atmospheric and instrumental errors at high frequencies on long baselines were removed (for details, see Reid & Menten 1990 and Torrelles et al. 1996), and the signal-to-noise ratio was improved.

We also used the data set at 7 mm from the VLA data archive (see also Gibb & Hoare 2007). In addition, we reanalyzed continuum observations at 2, 3.5, and 6 cm, which have been previously published (see Table 1). All observations were carried out in the A configuration. We recalibrated these data sets and made

![Radio-continuum contour maps consistently showing an elongated structure for S140 IRS 1A at several wavelengths. Contours are (a) $-3, 3, 5, 7, 9, 12, 15, \text{ and } 20 \times 200$ (1.3 cm; beam $0.11'' \times 0.09''$), (b) $-3, 3, 5, 7, 9, 11, \text{ and } 13 \times 170$ (2 cm; beam $0.12'' \times 0.10''$), (c) $-3, 3, 5, 7, 9, 12, 15, 20, 30, \text{ and } 40 \times 43$ (3.5 cm; beam $0.36'' \times 0.31''$), and (d) $-3, 3, 5, 7, 9, 12, 15, 20, 30, 40, \text{ and } 50 \times 40$ (6 cm; beam $0.37'' \times 0.31''$) mJy beam$^{-1}$, the rms noise of the maps. In all maps the beam is shown in the lower left corner. In order to make all continuum peaks of IRS 1A coincide, we have applied an offset of $(\alpha, \delta) = (-0.0017\,\text{h}, -0.007\,\text{deg}), (+0.0017\,\text{h}, +0.009\,\text{deg}), \text{ and } (+0.0016\,\text{h}, +0.014\,\text{deg})$ to the position of IRS 1A at 2, 3.5, and 6 cm, respectively. The crosses show the positions of the water masers detected in the region with their LSR velocity values (km s$^{-1}$) indicated in (b). The dashed and dotted lines in (c) indicate, respectively, the axes of the H$_2$ jet and CO outflow seen on large scales.]

**TABLE 1**

| Wavelength (cm) | Observation Date | HPBW (arcsec) | Reference |
|-----------------|------------------|---------------|----------|
| 0.7..............| 1996 Nov 1       | 0.04          | VLA data archive (project AH5980) |
| 1.3..............| 1999 Jun 29      | 0.1           | This paper |
| 2.................| 1987 Sep 12      | 0.1           | Schwartz (1989) |
| 3.5..............| 1992 Nov 24      | 0.3           | Tofani et al. (1995) |
| 6.................| 1987 Sep 12      | 0.3           | Schwartz (1989) |
new contour maps using the current procedures of AIPS. We used the physical parameters derived from these new contour maps for the discussion in this paper. Contour maps at 2 and 6 cm and their measured physical parameters are consistent with those published before by Schwartz (1989). However, the flux density estimated at 3.5 cm is different (about 50% lower) from that reported by Tofani et al. (1995), probably due to a typographical error.

3. OBSERVATIONAL RESULTS

Figure 1 shows the contour maps of S140 IRS 1 at centimeter wavelengths (1.3, 2.0, 3.5, and 6.0 cm). Given that other condensations are also detected around S140 IRS 1, hereafter we refer to S140 IRS 1 as S140 IRS 1A or just IRS 1A for clarity. This source appears spatially resolved at all wavelengths. The physical parameters of the radio source IRS 1A (position, flux density, deconvolved angular size, and position angle) were obtained from elliptical Gaussian fits using the AIPS task imfit and are given in Table 2. Contour maps at 1.3 and 2 cm have similar angular resolution (~0.1") and were made with natural and uniform weighting, respectively. On the other hand, contour maps at 3.5 and 6 cm have an angular resolution of ~0.3" (Fig. 1). For the map at 3.6 cm a Gaussian taper of 850 k fa was used, while at 6 cm a ROBUST = -1 parameter (Briggs 1995) of the AIPS task imagr was used.

In all contour maps (Fig. 1), IRS 1A shows a general elongated morphology in the northeast-southwest direction, similar to the orientation of the bipolar outflow observed in H2 toward IRS 1A in the 20°/200° direction (Preibisch & Smith 2002). In addition, our contour map at 1.3 cm with angular resolution of ~0.08" (ROBUST = 0 parameter was used in order to optimize the compromise between the signal-to-noise ratio and the angular resolution) shows a peak, at a level of 4 σ, located about 0.13" to the south of IRS 1A (Fig. 2). We refer to this peak as IRS 1B. Furthermore, three other continuum peaks (which we refer to as IRS 1C, IRS 1D, and IRS 1E) are also observed at 3.5 cm with an angular resolution of ~0.25" (Fig. 2). IRS 1C is located ~0.6" to the northeast of IRS 1A (Fig. 2) and is also detected at 2 cm with an angular resolution of ~0.15". IRS 1D and IRS 1E are located ~0.35" to the northeast and southwest of IRS 1A, respectively. Their main observed parameters are given in Table 2.

On the other hand, IRS 1A is detected at 7 mm (Fig. 3; flux density and deconvolved size are given in Table 2), while this is not the case for IRS 1B, 1C, 1D, or 1E. Although the 7 mm continuum emission is also elongated in the northeast-southwest direction like the centimeter emission (1.3, 2.3, 5.6 cm), the images do not have, within the error, the same position angle (the millimeter emission has a position angle of ~61°, while the centimeter emission has a position angle of ~44°). These results are consistent with those found very recently by Gibb & Hoare (2007).

The water-maser emission toward S140 IRS was in a period of minimum activity during our VLA observations, and we only detect three water maser features spatially associated with IRS 1A (Fig. 1). One of these maser features, with blueshifted velocity with respect to the molecular cloud velocity (approximately ~6.5 km s⁻¹; Zhou et al. 1993), is located close (0.1") to the IRS 1A continuum emission peak at 1.3 cm, while the other two maser features, with blueshifted velocity with respect to the molecular cloud velocity, are located ~0.5" and ~0.7" to the southwest of IRS 1A, respectively (see Fig. 1 and Table 3). Figure 9 from Trinidad et al. (2003) shows that the water maser emission toward S140 IRS was stronger (up to 46 Jy with at least seven features) a month before the VLA observations presented here. The position, velocity, and flux density of the three detected VLA water-maser features are given in Table 3.

4. DISCUSSION

The elongated morphology of IRS 1A is evident in the contour maps at all centimeter wavelengths (1.3, 2, 3.5, and 6 cm), suggesting a jetlike nature (see Fig. 1), similar to other possible radio jets associated with massive YSOs (e.g., Claussen et al. 1994; Rodríguez et al. 1994; Torrelles et al. 1996; Hofner et al. 1999; Gibb et al. 2003; Trinidad et al. 2003, 2005; Curiel et al. 2006; see Hoare 2006 and references therein). However, Hoare (2006), based on very detailed 6 cm continuum multiepoch observations with MERLIN, has proposed that the continuum emission is produced by an equatorial wind. We discuss both of these possibilities below.

4.1. IRS 1A: A Thermal Radio Jet?

In order to investigate whether or not IRS 1A is a thermal jet, we have calculated, following the formalism of Reynolds (1986), the dependence of the flux density and the deconvolved angular size of the major axis of the jet with the frequency. For the case of a thermal jet with constant velocity, temperature, and ionization fraction, the dependence of the flux density with the frequency is \( S_\nu \propto \nu^\alpha \) (\( \alpha = 1.3 - 0.7/\varepsilon \); eq. [14] of Reynolds 1986), while that for the deconvolved angular size of the major axis is \( \theta_{maj} \propto \nu^\beta \) (\( \beta = -0.7/\varepsilon \)). Under this formalism, \( \varepsilon \) is the power-law index that describes the dependence of the jet half-width, \( \psi \) (perpendicular to the major axis of the jet), as a function of the distance from the origin. For a conical jet, \( \varepsilon = 1 \), we get \( \alpha = 0.6 \) and \( \beta = -0.7 \).
obtained with MERLIN observations (Hoare 2006), a spectral index of about 0.6 ± 0.1 is obtained, which is consistent with that estimated using only VLA observations. In this way, we also note that the flux density and angular diameter of IRS 1A as measured with the VLA, with an angular resolution of about 0.35", and those measured with MERLIN (Hoare 2006), with an angular resolution of about 0.11", are consistent within 25%-30%. This result shows that changes of the angular diameter of the source are not due to an effect of angular resolution; that is, the larger angular size measured at low frequencies is not an effect of lower angular resolution than at higher frequencies.

Under the assumption that IRS 1A is a thermal jet, we can also estimate the ionized mass-loss rate (\( \dot{M} \)) and momentum rate (\( \dot{P} \)) deposited by IRS 1A into the ambient medium. Following Reynolds (1986) and using equation (3) given by Beltrán et al. (2001), for a pure hydrogen jet with constant velocity and ionization fraction, we have

\[
\left( \frac{\dot{M}}{10^{-6} M_\odot \text{ yr}^{-1}} \right) = 0.108 \left[ \frac{2 - \alpha}{1.3 - \alpha} \right]^{3/4} \left[ \frac{S_\nu}{\text{mJy}} \left( \frac{\nu}{10 \text{ GHz}} \right)^{-\alpha} \right]^{3/4} \left( \frac{V}{200 \text{ km s}^{-1}} \right) \left( \frac{\nu_{\text{m}}}{10 \text{ GHz}} \right)^{0.75\alpha - 0.45} \left( \frac{\theta_{\alpha}}{\text{rad}} \right)^{3/4} \left( \sin i \right)^{-1/4} \left( \frac{d}{\text{kpc}} \right)^{3/2} \left( \frac{T}{10^4 \text{ K}} \right)^{-0.075},
\]

where \( \alpha \) is the spectral index, \( S_\nu \) is the observed flux density at frequency \( \nu \), \( V \) is the terminal velocity of the jet, \( \theta_{\alpha} \) is the opening angle of the jet, and \( \nu_{\text{m}} \) is the frequency of maximum brightness.

From the multiepoch observations at 6 cm (Hoare 2006), it is known that the flux density of IRS 1A is not variable with time. Assuming that the flux density of IRS 1A has not changed significantly with time at other wavelengths either (the observations were made with a time span of about 12 yr; see Table 1), we roughly estimate a spectral index of \( \alpha = 0.5 \pm 0.1 \) by using the flux densities at 0.7, 1.3, 2, 3.6, and 6 cm (see Fig. 4). In addition, we also estimate the dependence of the angular size of the major axis of IRS 1A with frequency, where the parameter is \( \beta = 0.98 \pm 0.06 \) (see Fig. 4). Both indices \( \alpha \) and \( \beta \) seem to be consistent with free-free emission in the wavelength range 0.7–6 cm, produced either by a conical collimated ionized jet (\( \epsilon = 2/3 \), standard collimated jet) or by a conical ionized jet (\( \epsilon = 1 \), standard spherical jet; see Table 1 of Reynolds 1986). On the other hand, using the flux density of IRS 1A at 1.3 cm (this work) and that at 6 cm to estimate the ionized mass-loss rate (\( \dot{M} \)) and momentum rate (\( \dot{P} \)) deposited by IRS 1A into the ambient medium. Following Reynolds (1986) and using equation (3) given by Beltrán et al. (2001), for a pure hydrogen jet with constant velocity and ionization fraction, we have

\[
\left( \frac{\dot{M}}{10^{-6} M_\odot \text{ yr}^{-1}} \right) = 0.108 \left[ \frac{2 - \alpha}{1.3 - \alpha} \right]^{3/4} \left[ \frac{S_\nu}{\text{mJy}} \left( \frac{\nu}{10 \text{ GHz}} \right)^{-\alpha} \right]^{3/4} \left( \frac{V}{200 \text{ km s}^{-1}} \right) \left( \frac{\nu_{\text{m}}}{10 \text{ GHz}} \right)^{0.75\alpha - 0.45} \left( \frac{\theta_{\alpha}}{\text{rad}} \right)^{3/4} \left( \sin i \right)^{-1/4} \left( \frac{d}{\text{kpc}} \right)^{3/2} \left( \frac{T}{10^4 \text{ K}} \right)^{-0.075},
\]

where \( \alpha \) is the spectral index, \( S_\nu \) is the observed flux density at frequency \( \nu \), \( V \) is the terminal velocity of the jet, \( \theta_{\alpha} \) is the opening angle of the jet, and \( \nu_{\text{m}} \) is the frequency of maximum brightness.

\[
\left( \frac{\dot{M}}{10^{-6} M_\odot \text{ yr}^{-1}} \right) = 0.108 \left[ \frac{2 - \alpha}{1.3 - \alpha} \right]^{3/4} \left[ \frac{S_\nu}{\text{mJy}} \left( \frac{\nu}{10 \text{ GHz}} \right)^{-\alpha} \right]^{3/4} \left( \frac{V}{200 \text{ km s}^{-1}} \right) \left( \frac{\nu_{\text{m}}}{10 \text{ GHz}} \right)^{0.75\alpha - 0.45} \left( \frac{\theta_{\alpha}}{\text{rad}} \right)^{3/4} \left( \sin i \right)^{-1/4} \left( \frac{d}{\text{kpc}} \right)^{3/2} \left( \frac{T}{10^4 \text{ K}} \right)^{-0.075},
\]

where \( \alpha \) is the spectral index, \( S_\nu \) is the observed flux density at frequency \( \nu \), \( V \) is the terminal velocity of the jet, \( \theta_{\alpha} \) is the opening angle of the jet, and \( \nu_{\text{m}} \) is the frequency of maximum brightness.

| \( \alpha \) (B1950.0) | \( \delta \) (B1950.0) | \( V_{\text{LSR}} \) (km s\(^{-1}\)) | Flux Density (Jy) |
|-------------------|-------------------|-------------------|-----------------|
| 22 17 41.099 | 63 03 41.64 | 7.7 | 0.35 |
| 22 17 41.024 | 63 03 41.48 | –16.0 | 2.29 |
| 22 17 40.999 | 63 03 41.42 | –13.4 | 1.44 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
is given in GHz, and the deconvolved size of the major axis
arcseconds. The opening angle is approximately estimated using \( \theta_\text{maj} = 2 \tan^{-1}(\theta_\text{min}/\theta_\text{maj}) \).

Then, assuming an inclination angle of the jet axis relative to the
line of sight \( i = 60^\circ \), a distance of 910 pc, an electron
temperature of \( 10^4 \) K, a lower limit for \( v_\text{m} \) (=22.2 GHz), and a
terminal velocity of \( \sim 500 \) km s\(^{-1}\), we determine the mass-loss rate
(\( M \)) and momentum rate (\( \dot{P} \)) deposited by IRS 1A into the
ambient medium as \( \sim 9 \times 10^{-7} \) \( M_\odot \) yr\(^{-1}\) and
\( \sim 4.5 \times 10^{-4} \) \( M_\odot \) yr\(^{-1}\) km s\(^{-1}\); respectively. These values are similar to those obtained
for the thermal jets associated with other massive YSOs (e.g.,
Cep A W2 and HH 80). On the other hand, using the correlation
(momentum rate vs. radio continuum luminosity) given by Anglada
(1996) to estimate the momentum rate, we find a value about 2
orders of magnitude larger than that estimated using the formalism
of Reynolds. This result suggests that Anglada’s correlation is
valid only for low-luminosity objects and cannot be extrapolated
to high-luminosity sources.

We have also detected four condensations almost aligned along
the major axis of IRS 1A (see Fig. 2). One continuum peak (IRS
1B) is detected at 1.3 cm, while the other three continuum peaks
(IRS 1C, 1D, and 1E) are detected at 3.5 cm. As IRS 1B is
detected only at 1.3 cm (although IRS 1B and 1E are located to the
southwest of IRS 1A, both continuum peaks are not spatially co-
incident), we are not able to estimate its spectral index, which
could have helped us to investigate whether it is a condensation
ejected by IRS 1A or, alternatively, an independent source. The
continuum peaks IRS 1D and 1E are almost symmetrically located
with respect to IRS 1A (see Fig. 2), and both condensations have
similar peak flux densities, which could suggest that they are con-
densations ejected by IRS 1A, as could be expected for a thermal
jet. Multiepoch observations (e.g., at 3.5 cm) to measure possible
proper motions of IRS 1D and 1E could test whether these are con-
densations ejected by the jet. On the other hand, the condensation
IRS 1C does not have a counterpart on the symmetrically opposite
side, as in the case of the pair formed by 1D and 1E. In addition,
IRS 1C appears misaligned with respect to the 1D-1A-1E system
(see Fig. 2). If IRS 1C were also ejected by the jet IRS 1A, this
could indicate that IRS 1A is precessing. Alternatively, IRS 1C
could be an independent source. In this way, IRS 1C seems to
coincide spatially, within positional error, with the clump to the north-
northeast detected by Hoare (2006) at 6 cm wavelength. Using
the peak flux densities at 3.5 (this work) and 6 cm (Hoare 2006),
we have roughly estimated a spectral index for IRS 1C of \( \sim -0.4 \),
which suggest that the continuum emission of IRS 1C is being pro-
duced by partially thick thermal free-free emission. In addition,
Hoare (2006) has reported possible proper motion of the north-
est-north clump with a tangential velocity of 120 km s\(^{-1}\) moving
toward the east. However, due to this high value of the velocity,
Hoare (2006) opens the possibility that the proper motion is not
due to real physical motion but to a traveling illuminating wave.

The overall radio continuum properties of IRS 1A indicate that
it could be a thermal jet associated with a high-mass YSO. In ad-
dition, the position angle of the elongated structure at centimeter
wavelengths (\( \sim 44^\circ \); Table 2) suggests that IRS 1A could be the
driving source of the bipolar molecular outflow seen in H\(_2\) in the
direction 20°/200°. Under this scenario and assuming that the con-
densation IRS 1C is an independent source, we speculate that this
newly detected source (IRS 1C) could be the driving source of the
other bipolar molecular outflow observed in the direction 160°/
340°. If this is the case, two close, independent, and almost per-
pendicular jets could be the driving sources of the two bipolar out-
flows observed in the region (see Fig. 2). Perpendicular thermal
jets have been observed in low-mass star-forming regions (e.g.,
HH 111; Reipurth et al. 1999).

In addition, all water maser features detected toward S140 IRS
are associated with IRS 1A, assuming that IRS 1E is not a stellar
object but was ejected from IRS 1A (see Figs. 1 and 2). The esti-
imated mass for IRS 1A, assuming that the masers are bound grav-
itationally, is \( \gtrsim 60 \) \( M_\odot \), which is greater than the mass estimated
from its luminosity (\( \sim 10 \) \( M_\odot \)). This result indicates that the water
maser features are not associated with a circumstellar disk; instead,
the water masers are tracing unbound motions, which is consistent
with IRS 1A being a thermal jet. Further observations with high
angular resolution and proper-motion studies will be needed to
study in detail the three-dimensional (spatiokinematic) distribu-
tion of the water masers in the region, which will help us to under-
stand the nature of IRS 1A and possibly discriminate between the
thermal jet and equatorial wind models (see below).
4.2. IRS 1A: An Equatorial Wind?

Using high angular resolution multipole observations at 6 cm toward IRS 1A, Hoare (2006) proposed that IRS 1A is an equatorial wind driven by radiation pressure from a central star and inner disk acting on the gas in the surface layers of the disk, and perpendicular to the CO bipolar outflow observed in the direction $160^\circ/340^\circ$. This scenario is supported by two facts: first, the location and extension perpendicular to the major axis of IRS 1A of a small-scale, monopolar, near-IR reflection nebula at the base of the blueshifted lobe of the molecular outflow, and second, the small outward proper motion of a continuum clump in the direction $160^\circ/340^\circ$, as would be expected for a jet.

The results of Hoare (2006) are opposed to the picture of the multiple jets described above for IRS 1A. However, our observational results could also be consistent with IRS 1A being an equatorial wind. As mentioned above (§ 4.1), there are two condensations (IRS 1D and 1E) located symmetrically on opposite sides of the central source, IRS 1A, and under the equatorial wind model IRS 1D and 1E could be tracing the outer border of the wind within a disk with a diameter of $\sim$650 AU.

Unfortunately, with the present data we cannot discriminate between the two proposed models for IRS 1A (jet vs. equatorial wind). However, we note that the presence of the outflow in the $20^\circ/200^\circ$ direction (in addition to the outflow in the $160^\circ/340^\circ$ direction) requires at least two independent powering YSOs in the region. In this way, within the equatorial-wind scenario IRS 1A would be the exciting source of the $160^\circ/340^\circ$ outflow (as proposed by Hoare 2006), while the new detected source IRS 1C would power the $20^\circ/200^\circ$ outflow.

Additional observations are required to discriminate in a more definitive way between the equatorial wind and the thermal jet scenarios. Any detection of large proper motions (hundreds of km s$^{-1}$) in the IRS 1D and 1E condensations in the northeast-southwest direction would favor the jet hypothesis. This test would require sensitive, high angular resolution continuum observations over several years. On the other hand, the study of the high-velocity molecular gas in the vicinity of the source IRS 1A could reveal the wide-angle outflow expected from an equatorial wind. Any detection, with high angular resolution observations, of molecular gas correlated with the radio continuum source could trace the neutral part of the disk and also provide strong evidence favoring the equatorial-wind scenario. In addition, as we have mentioned before, proper-motion studies of the water masers observed in this region could be a powerful tool to discriminate between the two models. On the other hand, with the present theoretical models (e.g., Drew et al. 1998; Lugo et al. 2004), we cannot discriminate between the jet and equatorial-wind models. However, we think that in an equatorial-wind model the angular diameter might be less sensitive to the frequency of the observation than in a jet model. In any case, more detailed theoretical studies will be necessary to address this important issue.

5. CONCLUSIONS

We have presented the results of 1.3 cm continuum and water-maser emission observations made with the VLA in its A configuration toward the S140 IRS region. We have also realigned continuum observations at 0.7, 2, 3.5, and 6 cm.

We observed IRS 1A at all wavelengths (0.7, 1.3, 2, 3.5, and 6 cm) and also detected four new continuum peaks (IRS 1B, 1C, 1D, and 1E). IRS 1B is only detected at 1.3 cm, while IRS 1C, 1D, and 1E are detected at 3.5 cm. IRS 1C, located $\sim$0.6$''$ to the northeast of IRS 1A, seems to be an independent source, while IRS 1D and 1E, located symmetrically with respect to IRS 1A, seem to be condensations associated with IRS 1A. Under this scenario, IRS 1A is not a single source, but a possible binary formed by IRS 1A and 1C. These two YSOs could explain the excitation of the two large bipolar molecular outflows observed toward S140 IRS 1. We have also detected three water masers toward IRS 1 that most probably are tracing unbound motions and are associated with the bipolar molecular outflow in the northeast-southwest direction.

In order to understand the nature of IRS 1A, we have analyzed two scenarios: the thermal jet model and the equatorial wind model. The elongated morphology and spectral indices, $\alpha$ and $\beta$, of the continuum emission in the 0.7–6 cm wavelength range are consistent with IRS 1A being a thermal jet. However, a photoevaporated disk (Hoare 2006; Gibb & Hoare 2007) could produce a similar morphology and spectral energy distribution. Proper-motion measurements of the detected continuum clumps IRS 1D and 1E would help to discriminate between these two scenarios (jet vs. equatorial wind). In addition, proper-motion measurements of the detected water masers would also be very valuable.

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