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RADIO CONTINUUM JETS FROM PROTOSTELLAR OBJECTS

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ABSTRACT

We have carried out a deep, 3.6 cm radio continuum survey of young outflow sources using the Very Large Array in its A configuration providing subarcsecond resolution. The eight regions observed are Haro 6-10 and L1527 IRS in Taurus, Haro 5a/6a in OMC 2/3, NGC 2023 MMS, NGC 2264 IRS1, HH 108 IRAS/MMS in Serpens, L1228, and L1251A. In combination with our similar and previously published maps of eight other star-forming regions, we find only one region with a single source, while the other 15 regions have on average 3.9 nearby sources. This supports the view that isolated star formation is rare. We have selected 21 objects, which are all young mostly Class I sources, and find a binary frequency of 33% in the separation range from 0″.5 to 12″. This is within the uncertainties comparable to the observed binary frequency among T Tauri stars in a similar separation range. Seven of the 21 sources drive giant Herbig-Haro flows. Four of these seven are known to have companions (three are triple systems), corresponding to 57%. We discuss these results in relation to the hypothesis that giant Herbig-Haro flows are driven by disintegrating multiple systems.

Key words: binaries: general — ISM: jets and outflows — radio continuum: ISM — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

Radio continuum emission at centimeter wavelengths has been found in association with the driving sources of many outflows in star-forming regions (e.g., Anglada 1995). In fact, almost all outflow sources appear to present centimeter emission above the 0.1 mJy level (e.g., Rodríguez & Reipurth 1998). Despite the weakness of this emission, it can be observed at high angular resolution and with current sensitive interferometers such as the Very Large Array (VLA). This radio continuum emission appears to originate in shock-ionized gas very close to the outflow exciting source (Anglada et al. 1992, 1998), and since it remains unaffected by extinction it allows us to investigate the properties of the region closest to the origin of the outflow. Subarcsecond angular resolution observations reveal that the centimeter emission traces collimated partially ionized jets extending typically to distances 10–100 AU from the exciting source, corresponding to material ejected from the protostar with dynamical ages of the order of a few years or less (Anglada 1996; Rodríguez 1997). In addition, such sensitive high angular resolution observations of the centimeter radio continuum emission can trace the presence of deeply embedded close protobinary systems (e.g., Rodríguez et al. 1998), allowing to test the frequency of these systems and their incidence on the development of the outflow activity (Reipurth 2000).

In this paper, we present new sensitive high angular resolution observations at 3.6 cm of eight star-forming regions with signs of outflow activity. These observations complement the survey initiated by Reipurth et al. (2002) in order to investigate the incidence of radio jets, as well as the properties, such as multiplicity and variability, of young deeply embedded objects.

2. OBSERVATIONS

We have used the NRAO[5] VLA in its A array configuration to observe eight regions of deeply embedded protostars at 3.6 cm, all of which are known to drive outflows. The sources L1527, Haro 5a/6a (OMC 2/3), and NGC 2264 IRS1 were observed on 2002 February 8 and March 1 and 4, while the sources Haro 6-10 and NGC 2023 MMS were observed on 2002 March 2, 3, and 8. Finally, the sources HH 108 IRAS/MMS, L1228, and L1251A were observed on 2002 March 5, 8, and 9.

We searched for time variability in the sources detected by comparing their flux densities for the three epochs observed. Except for VLA 18 in the OMC 2/3 region (see § 3.3), no source showed clear variability. We searched unsuccessfully for linear and circular polarization in the sources detected, except for a jet detected in NGC 2264, which is discussed in § 3.5. Typical 4 σ upper limits of 30 μJy were set for the Q, U, and V Stokes parameters.

In Table 1, we list the observational parameters for each source. Source properties and very accurate positions are listed in Table 2. There was no evidence of time variability in most of the regions observed on different days, and the flux densities given in Table 2 are the average over all the observations.

3. RESULTS

In the following, we discuss the radio continuum detections in the eight outflow regions observed in relation to the young sources already known to exist there.

3.1. *Haro 6-10*

The young star Haro 6-10, also known as GV Tau, was first noted by Haro, Iriarte, & Chavira (1953) as an Hα emission

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TABLE 1
Regions Observed at 3.6 cm

Region	Phase Center (J2000.0) α	Phase Center (J2000.0) δ	Phase Calibrator[a]	Bootstrapped Flux Density (Jy)	rms Noise (μJy)	Synthesized Beam Size (arcsec)	Synthesized Beam P.A. (deg)
Haro 6-10	04 29 23.5	+24 32 58	0403+260	0.884 ± 0.006	7	0.29 × 0.26	−68
L1527	04 39 53.9	+26 03 10	0403+260	0.870 ± 0.017	8	0.29 × 0.27	+79
OMC 2/3 (Haro 5a/6a)	05 35 26.8	−05 03 56	0541−056	0.767 ± 0.026	7	0.35 × 0.29	+26
NGC 2023 MM	05 41 24.9	−02 18 09	0541−056	0.748 ± 0.004	9	0.32 × 0.28	−1
NGC 2264 IRS1	06 41 11.2	+09 29 25	0643+089	0.272 ± 0.012	8	0.30 × 0.29	−58
HH 108 IRAS/MMS	18 35 44.4	−00 33 05	1851+005	0.715 ± 0.005	9	0.35 × 0.29	−36
L1228	20 57 12.2	+77 35 43	2005+778	1.178 ± 0.019	7	0.31 × 0.29	−64
L1251A	22 35 24.3	+75 17 27	2236+733	0.296 ± 0.017	8	0.31 × 0.29	−63

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] The flux density of the phase calibrators is the average of the three observing sessions.

star. It is located in the Taurus clouds at a distance of 140 pc and is associated with a small dense ammonia core (Anglada et al. 1989). The spectrum of Haro 6-10 is mainly a red continuum, with possible evidence for a K3–K5 spectral type (Goodrich 1986). An infrared companion was discovered by Leinert & Haas (1989) about an arcsecond north of Haro 6-10 and further studied by Ménard et al. (1993) and Koresko, Herbst, & Leinert (1997). Both components vary significantly in the infrared (e.g., Leinert et al. 2001). Haro 6-10 is associated with the little group of Herbig-Haro objects known as HH 184, as well as the giant bipolar Herbig-Haro flow HH 410/411 stretching over 1.6 pc (Devine et al. 1999). Movsessian & Magakian (1999) found a small jet associated with Haro 6-10 itself.

Our high-resolution 3.6 cm VLA A map in Figure 1*a* shows two sources, which are coincident with the two components of the Haro 6-10 binary. From this we determine, for the epoch 2002.2, a very precise projected separation of the components of 1.″316, with the companion at a position angle of 354.°6. It is noteworthy that the southern, optical component, VLA 1, is much brighter than the northern, VLA 2. Furthermore, VLA 1 is very clearly elongated at a position angle of 191°, strongly suggesting the presence of a compact radio jet (see Table 3). This is within the uncertainties the same as the position angle, 195°, of the small Herbig-Haro jet found by Movsessian & Magakian (1999), but rather significantly different from the well-determined position angle of 228° for the HH 410 giant flow. As discussed by Devine et al. (1999), there is evidence that the Herbig-Haro flow has recently undergone considerable precession, and whereas the giant Herbig-Haro flow indicates the initial outflow angle, the VLA jet reveals the current position angle.

Both Devine et al. (1999) and Movsessian & Magakian (1999) favored the infrared source as the driving source of the outflow activity in this region. The present observations strongly suggest that this is not the case, and that the optical component, Haro 6-10 itself, is the driving source of this large outflow activity.

In a recent hypothesis for the formation of Herbig-Haro flows, Reipurth (2000) has suggested that giant Herbig-Haro flows originate when a nonhierarchical triple system breaks up and ejects one of the components, in the process forming a highly eccentric binary system from the remaining components. The orbital motion in the viscous environment of the circumstellar disks and remnant infalling envelope leads to rapid evolution and shrinking of the orbit. At each periastron passage, an outburst of activity is triggered, so that Herbig-Haro knots are ejected with increasing frequency. At the same time, tidal forces become stronger as the components move toward each other, leading to deviations from the initially stable outflow axis. This scenario is consistent with the structure of the Herbig-Haro flows around Haro 6-10.

A prediction of the above hypothesis is that Haro 6-10 should be a close binary itself. We do not see direct evidence for such a companion in our data with normal processing. However, it is interesting that there is an elongation on either side of the radio jet seen in several contours (Fig. 1*a*). We have, therefore, applied a gentle deconvolution to the map, and show the result in Figure 1*b*. The deconvolution strongly indicates the presence of a second radio jet at right angles to the VLA 1 jet. This second jet is perfectly symmetric around a central condensation. Since this condensation is located along the axis of the VLA 1 radio jet, we cannot, on the basis of the present data, state with certainty whether it is a knot in the VLA 1 radio jet, or rather is a stellar companion driving the east-west jet. However, it would be a curious coincidence if there should be an unrelated knot just at the center of the second small jet, and we presume that future observations will confirm the presence of a stellar companion, which we in the following designate VLA 1B.

The radio jet from VLA 1B has a position angle of 97° and a total extent of 0.″7, corresponding to a dimension of 100 AU in projection at the assumed 140 pc distance of the Taurus clouds. With a typical jet velocity of 100 km s^{-1}, this suggests that the two blobs in the VLA 1B jet were launched only 2 yr ago. The putative companion is separated from VLA 1 by 0.″27. A rather similar case of a double radio jet is seen for the HH 111 source (Rodríguez & Reipurth 1994; Reipurth et al. 1999b).

Devine et al. (1999) noted that the HH 184 flow consists of two independent flows, HH 184A–E, and HH 184F–G, which cannot be driven by the same source. They also noted that the ratio of the projected distances from Haro 6-10 to HH 184A and 184B is almost exactly the ratio of the distances to HH 184F and 184G, suggesting that these independent pairs of shock events were generated simultaneously, as would be expected at the periastron passages of a binary.

The projected distance between the two components within VLA 1 is 38 AU and the projected distance between VLA 1 and 2 is 184 AU. If these numbers reflect their true separations, then the system is dynamically unstable and will split

TABLE 2
PARAMETERS OF THE 3.6 cm VLA Sources

Object	Position[a] (J2000.0) α	δ	Other Designation	Flux[b] (mJy)	Distance (pc)
		Haro 6-10			
VLA 2	04 29 23.724	+24 33 01.43	Haro 6-10 N	0.10	140
VLA 1	04 29 23.733	+24 33 00.12	Haro 6-10 S	1.10	140
VLA 3	04 29 25.954	+24 32 34.09	...	0.12	140
		L1527			
VLA 1	04 39 53.867	+26 03 09.85	IRAS 04368+2557	1.01	140
VLA 3	04 39 59.856	+26 02 06.85	...	1.71	140
		OMC 2/3			
VLA 15	05 35 25.965	−05 05 43.45	...	1.29	460
VLA 4	05 35 26.560	−05 03 55.08	IRAS 05329−0505	0.83	460
VLA 16	05 35 28.191	−05 03 41.19	...	0.17	460
VLA 17	05 35 29.224	−05 05 44.23	...	1.57	460
VLA 18	05 35 33.645	−05 03 08.00	...	0.64[c]	460
		NGC 2023 MM			
VLA 3	05 41 21.69	−02 11 07.6	...	~50	460
VLA 1	05 41 24.931	−02 18 06.67	NGC 2023 MM1	0.14	460
VLA 2	05 41 29.208	−02 16 47.39	...	0.13	460
		NGC 2264 MM			
VLA 1	06 41 10.024	+09 29 44.55	...	0.18	800
VLA 2	06 41 10.062	+09 29 21.78	MMS 4	0.62	800
VLA 3	06 41 10.117	+09 29 36.09	MMS 5	0.11	800
VLA 4	06 41 10.166	+09 29 33.67	IRS1	0.50	800
VLA 5	06 41 11.274	+09 29 05.93	...	0.12	800
VLA 6	06 41 12.630	+09 29 04.47	...	0.07	800
VLA 7	06 41 12.697	+09 29 03.83	...	0.19	800
VLA 8	06 41 13.047	+09 27 31.72	...	0.21	800
		HH 108			
VLA 1	18 35 42.135	−00 33 18.30	IRAS 18331−0035	0.42	310
VLA 2	18 35 46.382	−00 31 43.38	...	0.17	310
		L1228			
VLA 4	20 57 06.703	+77 36 56.07	HH 200 IRS	0.17	200
VLA 1	20 57 12.924	+77 35 43.68	IRAS 20582+7724	0.12	200
VLA 2	20 57 24.75	+77 33 28.4	...	5.1	200
VLA 3	20 57 27.809	+77 34 59.90	...	0.42	200
		L1251A			
VLA 6	22 35 23.421	+75 17 07.91	VLA A	0.16	300
VLA 10	22 35 24.140	+75 17 04.89	...	0.14	300
VLA 7	22 35 24.948	+75 17 11.42	VLA B	0.15	300
VLA 11	22 35 29.174	+75 17 08.13	VLA D	0.11	300

[a] The absolute positional error is estimated to be $\sim0''.05$.
[b] Total flux density corrected for primary beam response.
[c] Variable source. Flux density corresponds to the value observed on 2002 Feburary 8. The source was not detected on 2002 March 1 and 2 above a 3 σ level of 0.06 mJy.

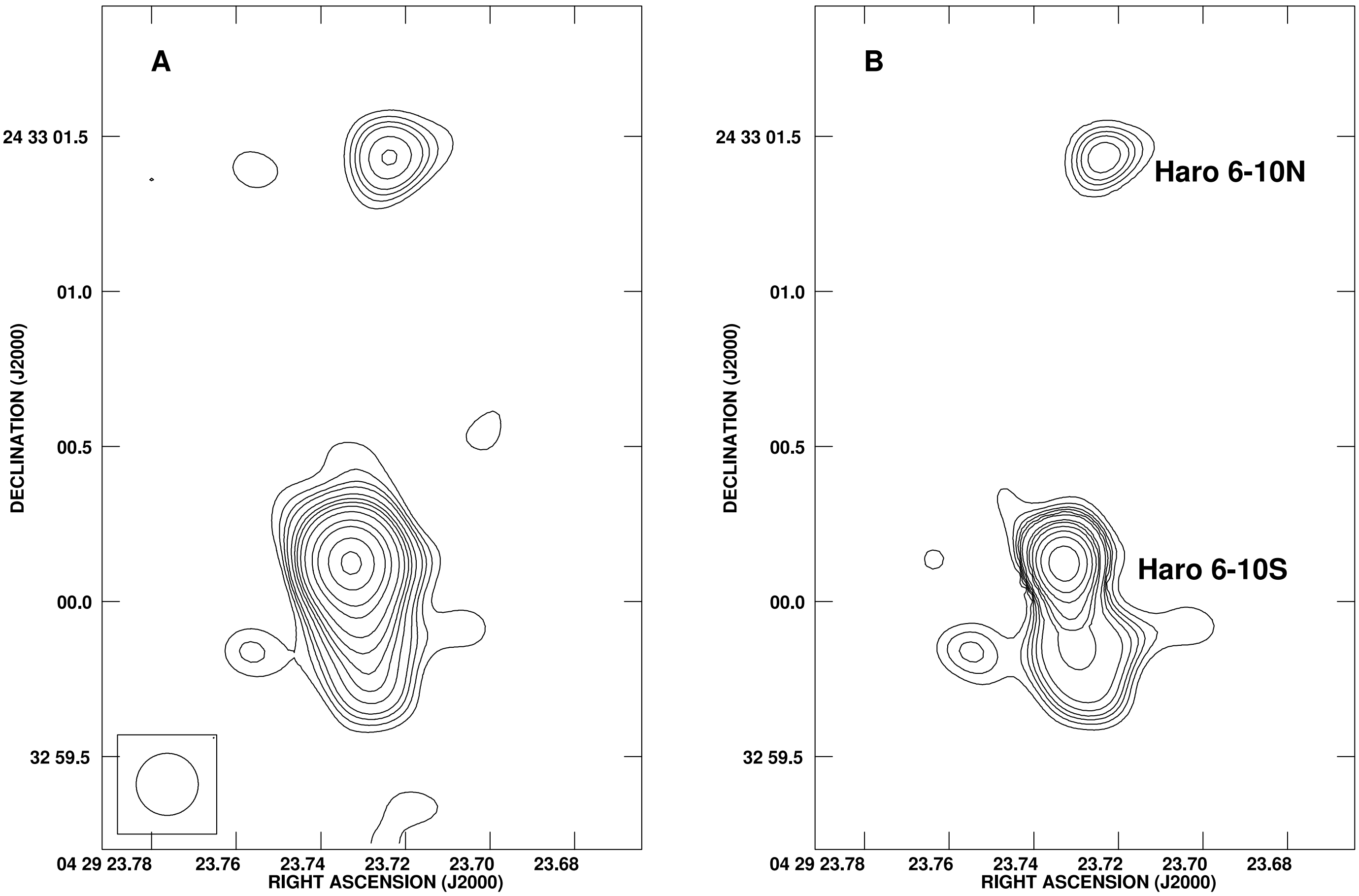

FIG. 1.—Region of 1″.8 × 2″.7 around Haro 6-10. The optical star is to the south, and the infrared companion is to the north. (*a*) A normal, clean map, while (*b*) has been lightly deconvolved using the maximum entropy method of Cornwell & Evans (1985). The southern source shows evidence for a close companion that drives a small bipolar jet. The half-power contour of the beam is shown in the bottom left corner. Contour levels for the left panel are −4, −3, 3, 4, 5, 6, 8, 10, 12, 15, 20, 30, 40, 60, 80 × 7 μJy beam^{-1}, the rms noise of the image. Contour levels for the right panel are 6, 8, 10, 12, 15, 20, 40, 60, 100, 200, 400, 800 × 10^{-8} Jy pixel^{-1}.

up. VLA 2 may, therefore, be moving away from VLA 1, either into a distant bound orbit or a complete escape. If the close triple encounter that started this break up occurred when the HH 410 bow shock was formed, then assuming a mean tangential velocity of HH 410 of, say, 100–200 km s^{-1}, we see that this break up occurred about 4000–8000 yr ago. This suggests that the current projected velocity of VLA 2 away from VLA 1 should be about 0.1–0.2 km s^{-1}, consistent with theoretical expectations (Delgado-Donate, Clarke, & Bate 2003). A more distant third source, VLA 3, is also detected, but it could be a background object.

3.2. *L1527*

IRAS 04368+2557 is a low-luminosity object embedded in the L1527 cloud in Taurus, and numerous studies exist at millimeter and submillimeter wavelengths. It is a Class 0 source (e.g., Chini et al. 2001), with no near-infrared counterpart. Only a bipolar reflection nebula is seen in the near-infrared, along the axis of a compact CO outflow oriented east-west and lying in the plane of the sky (Tamura et al. 1996). Herbig-Haro emission knots, known as HH 192, are found on either side of the source, again along the east-west outflow axis (e.g., Gómez, Whitney, & Kenyon 1997). Three VLA sources were found in the region at 3.6 cm, one of which, VLA 1, coincides with IRAS 04368+2557 (Rodríguez & Reipurth 1998). These authors also observed VLA 1 at 2 cm and found evidence for a small radio jet at a position angle of 110°.

Our 3.6 cm A configuration map is seen in Figure 2. The innermost bright core is slightly extended along a position angle of 110° (Table 3), just as seen in the lower resolution 2 cm observations. Additionally, a curved 1″ long radio jet is seen in Figure 2 to extend toward the east, the inner contour of which starts out at a position angle of 80°. Recently, Loinard et al. (2002) found VLA 1 to be a very close (0″.2) binary at 7 mm. Perhaps the binary is producing two separate outflows simultaneously, with a 30° difference in outflow orientation. Alternatively we see very rapid changes in flow direction.

TABLE 3

PARAMETERS OF RESOLVED VLA SOURCES

Object	Deconvolved Size (arcsec)	P.A. (deg)
Haro 6-10 VLA 1	0.22 ± 0.01 × 0.09 ± 0.01	+191 ± 3
L1527 VLA 1	0.15 ± 0.01 × 0.11 ± 0.01	+110 ± 10
OMC 2/3 VLA 4	0.55 ± 0.03 × 0.19 ± 0.02	+76 ± 3
OMC 2/3 VLA 16	0.50 ± 0.09 × 0.23 ± 0.12	+76 ± 16
NGC 2264 MM VLA 2	0.40 ± 0.01 × 0.14 ± 0.02	+117 ± 3
NGC 2264 MM VLA 7	0.81 ± 0.12 × 0.31 ± 0.10	+45 ± 8
HH 108 VLA 1	0.72 ± 0.07 × 0.25 ± 0.07	+226 ± 5
L1251A VLA 10	0.43 ± 0.07 × 0.25 ± 0.07	+53 ± 15
L1251A VLA 7	0.48 ± 0.06 × 0.17 ± 0.07	+126 ± 8

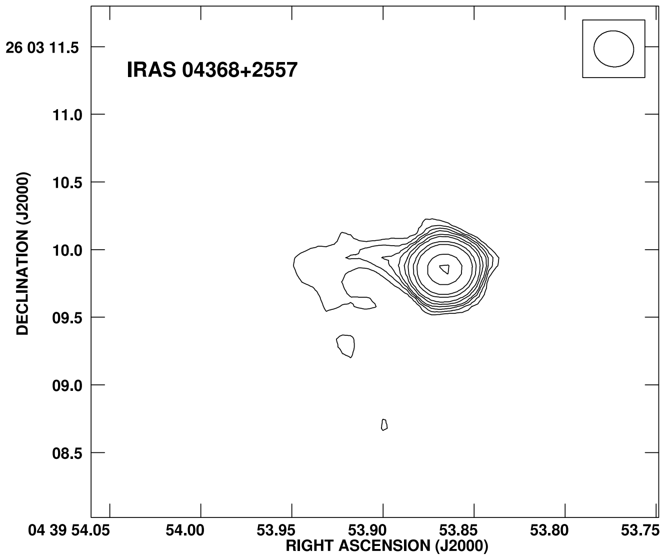

FIG. 2.—IRAS 04368+2557 source in L1527 is seen to drive a curving radio continuum jet. The source is unresolved at 3.6 cm, but Loinard et al. (2002) find it to be a close binary at 7 mm. The half-power contour of the beam is shown in the top right corner. Contour levels are −4, −3, 3, 4, 5, 6, 8, 10, 15, 20, 40, 60 × 8 μJy beam^{-1}, the rms noise of the image.

3.3. *OMC 2/3 (Haro 5a/6a)*

IRAS 05329−0505 is a rather luminous (∼50 $L_\odot$) embedded Class I source in the region between M42 and M43 (Wolstencroft et al. 1986) and is a bright millimeter continuum source (MMS 7; Chini et al. 1997). Based on near-infrared spectroscopy, Reipurth & Aspin (1997) suggested that the source is likely to be in an FU Orionis state. Optical images show a prominent east-west oriented bipolar reflection nebula called Haro 5a/6a (Haro 1953), and Reipurth, Bally, & Devine (1997) associated the source with a giant Herbig-Haro flow comprising HH 41/42 to the east and HH 295 to the west. Infrared images show a small molecular hydrogen jet, and CO maps a single elongated outflow lobe west of the source (Yu, Bally, & Devine 1997; Yu et al. 2000).

Low-resolution radio continuum maps of the OMC 2/3 region were presented by Reipurth, Rodríguez, & Chini (1999a), who detected IRAS 05329−0505 at 3.6 cm, and labelled it VLA 4. Our high-resolution map is seen in Figure 3, and it shows clearly that VLA 4 is extended in a bipolar thermal radio jet. The overall extent is 3″, and assuming a typical outflow velocity of 100 km s^{-1} the two lobes are each about 30 yr old.

The eastern lobe shows interesting structure. If the principal flow axis is represented by a line between the core and the small knot outside the eastern lobe, then the position angle is 73°. Interestingly, the contours of the eastern lobe do not lie along this position angle, but gradually bend southward to a position angle of 79° before turning back again. We interpret this as precession or wiggling of the jet axis, suggesting that the source is a binary. The half-period is about 20 yr, suggesting that the binary is very close, with a semimajor axis of the order of 10 AU.

The western lobe is shorter and has a position angle of 248° if measured through the distant isolated knot, 5° different from the eastern lobe. Such a difference is often seen in flows with binary sources. However, additionally, a knot is seen 0″.6 southwest of the core at a position angle of 218°. Assuming that this knot is nonstellar, then it is in a location that cannot be part of the main flow, thus suggesting that we are seeing a second flow from the source, supporting the hypothesis that the source is a binary.

We have detected four other sources in the surroundings of VLA 4, which we label VLA 15–18, in continuation of the numbering scheme for the OMC 2/3 region employed by Reipurth et al. (1999a). One of these, VLA 16, is extended (Fig. 4). Another, VLA 18, showed strong variability, it was detected as a bright source on 2002 February 8 at a level of 0.64 ± 0.02 mJy but was not detected on 2002 March 1 and 4, with a 3σ upper limit of about 0.06 mJy. Presumably VLA 15–18 are likely to be young sources associated with the OMC 2/3 star-forming region.

3.4. *NGC 2023 MM*

NGC 2023 is a bright reflection nebula surrounding the B1.5 star HD 37903 in the L1630 cloud northeast of the Horsehead Nebula. It is a region rich in low-mass star formation as evidenced by numerous infrared sources (e.g., DePoy et al. 1990) and several Herbig-Haro objects (Malin, Ogura, & Walsh 1987). The region was studied in several millimeter wavelength transitions by White et al. (1990) and in the 1300 μm continuum by Launhardt et al. (1996). These latter authors first noted a 1300 μm source near the LBS 36 core, which they named LBS 36 SM 1. Sandell et al. (1999) studied the region at various submillimeter wavelengths and found that the source, which they call NGC 2023 MM 1, is a very cold Class 0 source driving a large, very well collimated molecular outflow.

Our 3.6 cm map of the region detects a radio continuum source, VLA 1, only 3″ from the more uncertain submillimeter position listed by Sandell et al. (1999), and we give position and flux density in Table 2. It is a rather faint source, and it shows no evidence of being extended. This is perhaps a bit surprising, since radio jets are seen from so many of the other sources in our survey, and this source is known to drive a

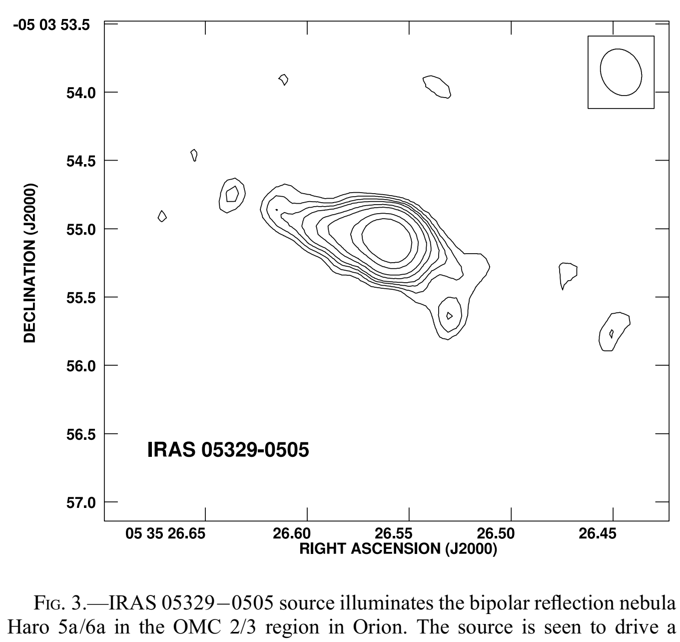

FIG. 3.—IRAS 05329−0505 source illuminates the bipolar reflection nebula Haro 5a/6a in the OMC 2/3 region in Orion. The source is seen to drive a bipolar radio jet that is precessing. An additional knot in the western lobe may represent a second outflow. The half-power contour of the beam is shown in the top right corner. Contour levels are −4, −3, 3, 4, 5, 6, 8, 10, 15, 20 × 7 μJy beam^{-1}, the rms noise of the image.

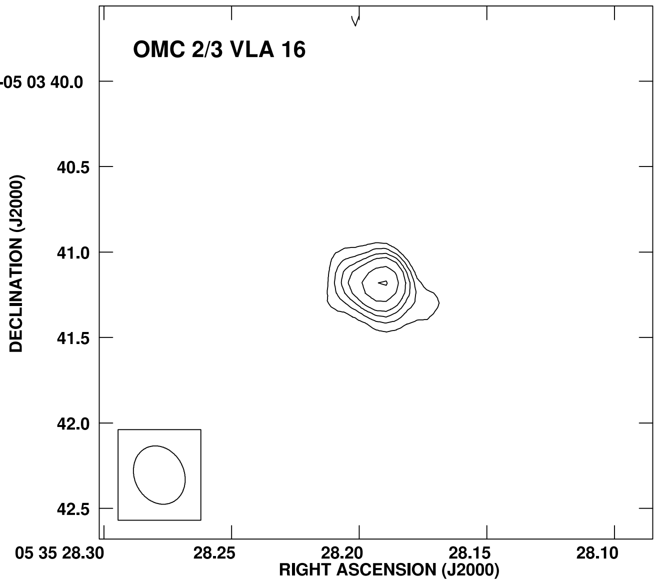

FIG. 4.—VLA 16 source in the OMC 2/3 region in Orion shows resolved structure. The half-power contour of the beam is shown in the bottom left corner. Contour levels are −4, −3, 3, 4, 5, 6, 8, 10 × 7 μJy beam^{-1}, the rms noise of the image.

particularly powerful, collimated outflow. Since the ejection of knots is highly episodic, it is possible that future observations will catch the source at a time when a radio jet will be visible.

Both Launhard et al. (1996) and Sandell et al. (1999) detected a second submillimeter source only 23″ southeast of MM 1. We see no sign of this source in our data.

Two other sources, NGC 2023 VLA 2 and 3, were detected in our map. VLA 2 is 100″ northeast of VLA 1, and we are not aware of any object at other wavelengths that coincide with this source. VLA 3 is a very bright source very far (7′.1) from the phase center of our map, so we can only give a rough estimate of about 50 mJy for its flux density. The radio source is 13″ from an *ASCA* source. Since the nominal position error of *ASCA* is 1′, the sources may well be the same. We note, furthermore, that there is a 1.4 GHz source detected in the NRAO VLA Sky Survey (Condon et al. 1998) with a flux density of 98.4 mJy and located ∼10″ from our 3.6 cm position. Further study is required to clarify the nature of this/these source(s).

3.5. *NGC 2264 IRS1*

Attention was drawn to a region north of the Cone Nebula in NGC 2264 by the discovery of a very luminous infrared source, IRS 1, by Allen (1972). Numerous subsequent studies have shown that this is a very young, embedded B-type star associated with several low-mass young stars (Thompson & Tokunaga 1978; Wolf-Chase & Gregersen 1997; Schreyer et al. 1997; Thompson et al. 1998). Submillimeter observations reveal that IRS 1 is located within a ridge of cold dust with several other embedded sources (Ward-Thompson et al. 2000; Williams & Garland 2002). Several compact sources were found at millimeter wavelengths by Nakano, Sugitani, & Morita (2003). We are probably here seeing a cluster in the early stages of formation. Outflow activity in this region has been mapped by Margulis, Lada, & Snell (1988) and by Schreyer et al. (1997), but their resolution is not sufficient to link the flows with particular sources in the cluster. Wang et al. (2002) detected molecular hydrogen flows in the region.

Our 3.6 cm high-resolution map reveals eight sources in the general region of IRS 1, seven of which are shown in Figure 5. Our source VLA 4, which has the second highest 3.6 cm flux among these sources, coincides with IRS 1. However, it shows no resolved components indicative of an outflow. We found the source on archival VLA data of the region from 1990 and 1995, and although the signal-to-noise is not good, it appears that the source has been constant within the errors.

Ward-Thompson et al. (2000) identified five compact submillimeter sources within the ridge, NGC 2264 MM, of cold dust around IRS 1. A close pair of sources, VLA 6 and 7, lie within the MMS 3 clump, although not at the nominal center position. VLA 5 is just east of MMS 3, toward the end of the main dust ridge. VLA 3 is located at the very center of the dust core MMS 5, and VLA 2 is at the center of MMS 4. The close association of these radio continuum sources with the submillimeter cores suggest that they are very young objects.

The source VLA 2, located at the center of MMS 4, is extended and is seen in Figure 6. The source is detected in archival VLA data from 1990 and 1995 and appears somewhat weaker than at present in the data from 1990 (0.41 ± 0.03 mJy). VLA 7, located just southeast of MMS 3, is also extended and shows considerable collimation (Fig. 7). In both cases, we are likely to see compact thermal jets emanating from these sources.

Three arcminutes southeast of IRS 1 we have found what we interpret to be a spectacular bipolar radio jet (Fig. 8), with a total 3.6 cm flux density of ∼13 mJy. The eastern part of the flow consists of numerous clumps, many of which are well resolved and show clear flattening perpendicular to the flow axis, as often seen in the internal working surfaces of optical Herbig-Haro jets. The flow is remarkably collimated and has an overall extent of about 28″. At our resolution, we identify eight knots in the eastern lobe. Assuming a typical jet velocity of about 100 km s^{-1}, this corresponds to about an ejection every 60 yr on average, consistent with timescales of jet formation in many other jets from young stellar objects. It is

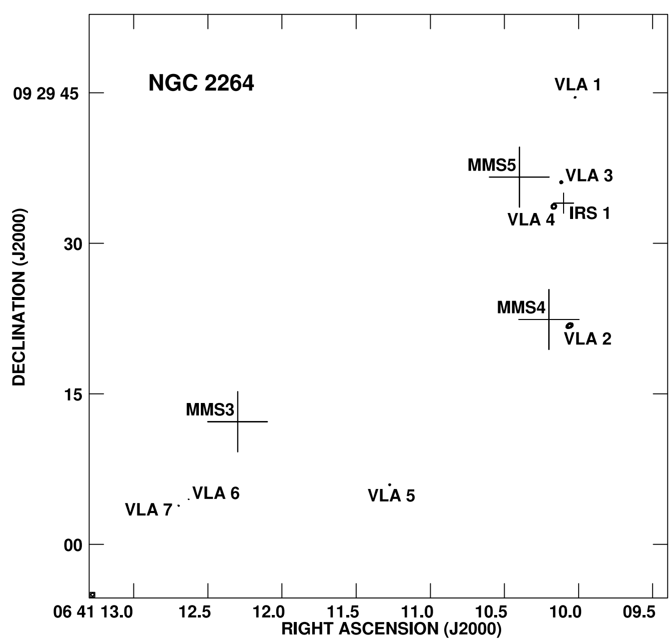

FIG. 5.—Region around IRS1 in NGC 2264. The 3.6 cm sources are shown as contours, and sources detected at other wavelengths are indicated with crosses. The position of IRS1 is from the *HST* study by Thompson et al. (1998).

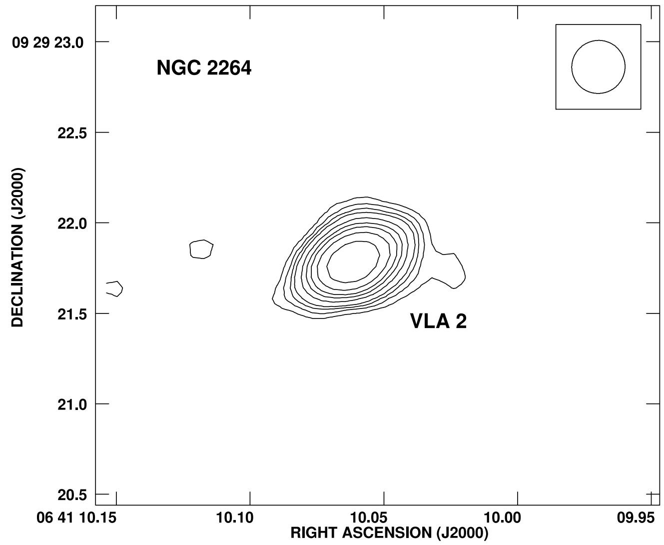

FIG. 6.—VLA 2 source in NGC 2264 shows a small thermal radio jet. The half-power contour of the beam is shown in the top right corner. Contour levels are −4, −3, 3, 4, 5, 6, 8, 10, 12, 15, 20, 40 × 9 μJy beam^{-1}, the rms noise of the image.

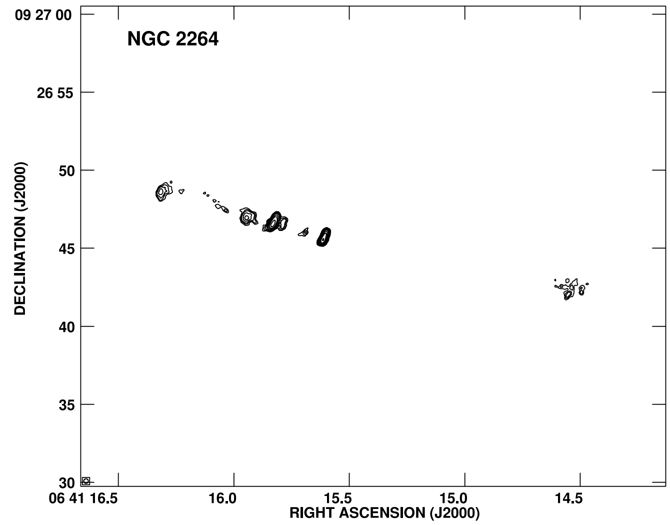

FIG. 8.—Giant radio jet just east of the Cone Nebula in NGC 2264. The lack of any infrared counterpart and the high polarization suggests that it may be an extragalactic jet seen by chance through the NGC 2264 region. The half-power contour of the beam is shown in the bottom left corner. Contour levels are −4, 4, 5, 6, 8, 10, 15, 20, 30, 40, 60 × 15 μJy beam^{-1}, the rms noise of the image.

curious that while the eastern lobe has numerous knots, the western lobe only shows a single large knot. Such asymmetries are not unknown, a well-known example is the radio continuum jet in the Serpens core (Curiel et al. 1993). Assuming that the driving source is located approximately midway between the two end points of the jet, we would expect it at about $\alpha = 06^{\rm h}41^{\rm m}154$, $\delta = +09°26'45''$ (J2000.0), which is not within the Cone Nebula itself, but just to the east of its head. We find nothing at this position in the radio continuum nor in the *IRAS* catalog. We have imaged the region at 2.2 μm at the University of Hawaii 2.2 m telescope and find no evidence for a source at this location. In the optical, we have examined *Hubble Space Telescope* (*HST*) images obtained of the Cone Nebula with the Advanced Camera System, and again there is no trace of any source or outflow activity.

Moreover, the jet shows strong linear polarization, with one knot having as much as 18% polarization. This points toward an extragalactic origin. If so, it is a curious coincidence that the jet is located within a region so rich in star formation. Repeated observations within the next 5 yr should resolve this issue by showing proper motions if the flow is indeed located within the NGC 2264 star-forming region.

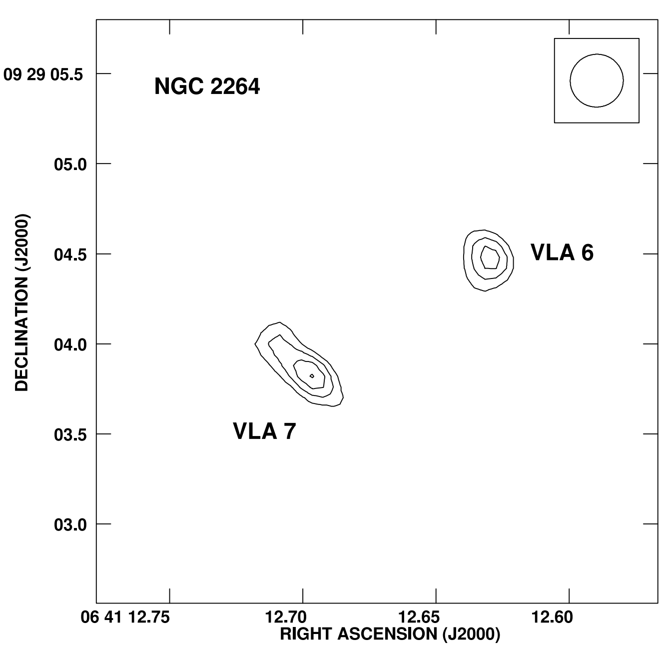

FIG. 7.—Two sources VLA 6 and 7 in NGC 2264. VLA 7 shows a small radio jet. The half-power contour of the beam is shown in the top right corner. Contour levels are −4, −3, 3, 4, 5, 6 × 8 μJy beam^{-1}, the rms noise of the image.

3.6. *HH 108 IRAS/MMS*

In a survey of the Serpens clouds, Reipurth & Eiroa (1992) found two Herbig-Haro objects, HH 108 and HH 109, aligned with the *IRAS* source 18331−0035, an embedded source with a luminosity of about 9 $L_{\odot}$ at the assumed distance of 310 pc. Subsequently, Chini et al. (1997) detected this source at submillimeter wavelengths and also found another nearby submillimeter source. This new source, HH 108 MMS, is a cold Class 0 source with a very low luminosity of about 1 $L_{\odot}$, in contrast to HH 108 IRAS, which is a Class I source. HH 108 MMS is only 70″ east-northeast of HH 108 IRAS, and the two are linked by a dust ridge detected at submillimeter wavelengths (Chini et al. 2001).

Our deep high resolution 3.6 cm observation clearly detected HH 108 IRAS. Figure 9 shows this source, here labelled HH 108 VLA 1, and reveals an associated subarcsecond radio jet. The position angle of this jet is about 226°, which may be compared with the position angle of 218° of a line drawn from HH 108 IRAS to HH 109, the closest of the two Herbig-Haro objects. This provides strong support for identifying HH 108 IRAS as the driving source of the HH 108/109 flow. Because of the proximity and relative location of HH 108 IRAS and HH 108 MMS, Chini et al. (1997) pointed out that there could be some ambiguity about which of the two sources was responsible for the Herbig-Haro flow, a matter that now appears settled.

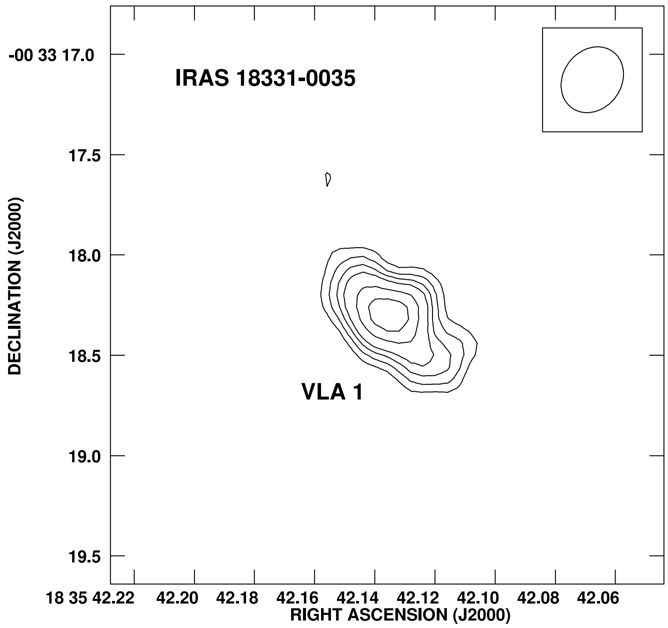

Fig. 9.—IRAS 18331−0035 source driving HH 108 shows a small bipolar radio jet. The half-power contour of the beam is shown in the top right corner. Contour levels are −4, −3, 3, 4, 5, 6, 8, 10 $\times$ 9 μJy beam^{-1}, the rms noise of the image.

In marked contrast, we did not detect any sign of HH 108 MMS at 3.6 cm. Besides the submillimeter detection, this source has only been seen at 14 μm in absorption against the diffuse background (Siebenmorgen & Krügel 2000). Attempts to detect infall signatures toward this source have been negative (Gregersen et al. 2000). Whereas other Class 0 sources are frequently detected in the centimeter radio continuum, we may in HH 108 MMS be seeing such an early stage in the protostellar formation that a hydrostatic core has not yet been formed.

A second VLA source, VLA 2, was found about 2′ north of VLA 1. We have no further information on this object, which could be a background source.

3.7. *L1228*

L1228 is a small cloud in the direction toward the Cepheus Flare and located at a distance of 200 pc (Kun 1998). Numerous Hα emission stars have been found around this cloud (Ogura & Sato 1990), as well as several molecular outflows (Haikala & Laureijs 1989; Tafalla & Myers 1997). A dense core, mapped in ammonia by Anglada, Sepúlveda, & Gómez (1997), contains at least two sources driving molecular outflows as well as the two Herbig-Haro flows HH 199 and HH 200 (Bally et al. 1995). HH 199 emerges from an embedded *IRAS* source, 20582+7724, a Class I source with an east-west oriented infrared reflection nebula (Hodapp 1994; Reipurth et al. 2000). Whereas the molecular outflow and the HH 199 flow have a position angle of about 60°, Hodapp (1994) and Bally et al. (1995) found a well-collimated H_2 emission flow at a position angle of about 100°. Either IRAS 20582+7724 is a possibly wide binary where each component is launching a separate flow, or one of the components of a very close binary is precessing rapidly, giving rise to the two very different flow angles. HH 200 is driven by an embedded T Tauri star about 1.′5 further to the northwest (Bally et al. 1995).

A low-resolution 3.6 cm survey of the L1228 cloud was made by Rodríguez & Reipurth (1996), who found two sources. One, VLA 1, is associated with the *IRAS* source, and the other, VLA 2, has no known counterpart but is located in the direction of the high extinction part of the L1228 cloud.

In our present, high-resolution 3.6 cm survey, we detected VLA 1 but did not find any companion, nor did we detect any radio jet associated with this source. VLA 2 is detected away from the phase center and therefore suffers significant bandwidth smearing. Its current flux density of about 5.1 mJy is much brighter than the 3.6 cm C array detection of 1.55 mJy reported by Rodríguez & Reipurth (1996).

We also detected two other sources, both within the L1228 cloud boundary, here named VLA 3 and 4. The source VLA 4 is located at the very edge of the optical reflection cavity that surrounds the driving source of the HH 200 flow and appears to be the same as the driving source. Nothing is known about possible counterparts to VLA 3.

3.8. *L1251A*

L1251 is a small cloud with active star formation at a distance of about 300 pc toward the Cepheus Flare (e.g., Kun & Prusti 1993; Kun 1998). L1251A is a star-forming region centered on the bright *IRAS* source 22343+7501, which is associated with a molecular outflow (Sato & Fukui 1989; Schwartz, Gee, & Huang 1988; Sato et al. 1994), an ammonia and CS core (Tóth & Walmsley 1996; Anglada et al. 1997; Morata et al. 1997), a Herbig-Haro object (HH 149, Balázs et al. 1992), and maser emission (e.g., Meehan et al. 1998).

We have detected four sources in the region around IRAS 22343+7501, three of which were known from previous studies. VLA 6 and 7 were first detected in the radio continuum by Meehan et al. (1998, their VLA A and B) and subsequently by Beltrán et al. (2001), whose nomenclature we adopt. VLA 11 is identical to VLA D of Meehan et al. (1998); it is outside the *IRAS* uncertainty ellipse and its nature is unknown. Finally, the high resolution of our VLA A maps has revealed a new source, VLA 10, close to VLA 6, with which it was blended in the earlier low-resolution data of Meehan et al. (1998). We are using the designations VLA 10 and 11 in continuation of the numbering scheme of Beltrán et al. (2001).

Rosvick & Davidge (1995) have found a small cluster of five near-infrared sources centered on IRAS 22343+7501. Unfortunately, their coordinates are inaccurate, but Meehan et al. (1998) suggest that VLA 6 corresponds to the very red and embedded source IRS D, while VLA 7 is the rather brighter source IRS A.

Two of our sources are clearly extended (Fig. 10). VLA 7 is a small subarcsecond radio jet at a position angle of about 126°, while VLA 10 is a similar sized jet at a position angle of about 53°. The molecular outflow found by Sato & Fukui (1989) extends over $\sim$10′ and has a position angle of about 45°, suggesting that VLA 10 could be its driving agent. On the other hand, the compact $\sim$2′ CO outflow reported by Schwartz et al. (1988) has its major axis at a position angle of about 140°, so that VLA 7 could be its driving source.

4. DISCUSSION

The motivation for the present study goes back to the VLA A array observations we performed of the HH 111 jet source, where we found a companion 3″ from the main source

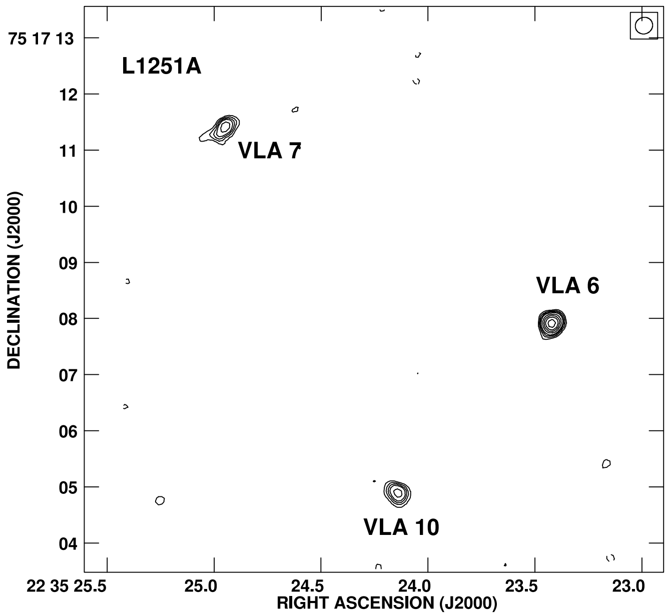

FIG. 10.—Three sources VLA 6, 7, and 10 in L1251A. VLA 7 and 10 are resolved and show tiny radio jets. The half-power contour of the beam is shown in the top right corner. Contour levels are −4, −3, 3, 4, 5, 6, 8, 10, 12, 15 × 8 μJy beam^{-1}, the rms noise of the image.

(Reipurth et al. 1999b, hereafter Paper I). These observations led to a general study of the multiplicity of giant Herbig-Haro energy sources through a variety of optical, infrared, and radio high-resolution techniques (Reipurth 2000), which found about 80% of the outflow sources to be binaries, and half of these higher order multiples. Extinction is a significant problem in studying embedded sources, and we therefore embarked on a major 3.6 cm radio continuum survey at the VLA in order to study the properties of deeply embedded protostars with outflows. The first part of this survey was published by Reipurth et al. (2002, hereafter Paper II), and the current paper (Paper III) completes the survey. A total of 16 regions of recent low-mass star formation, all containing outflow sources that are well studied at other wavelengths, were targeted in these three papers. All regions contain either Class I or, in a few cases, Class 0 sources. Altogether we detected 59 radio continuum sources. We cannot be certain that all of these sources are young, but based on statistical arguments (e.g., Rodríguez 1997) we are confident that a large majority are due to newborn stars. Of the 16 fields observed, just one field contained only a single object (the source in the B335 Bok globule), the remaining 15 fields contained two or more objects, with an average of 3.9 nearby sources per field. We conclude, in agreement with numerous other studies of low-mass star-forming regions, that *isolated star formation is extremely rare*.

The question of the binary fraction among embedded outflow sources is difficult to determine based on our present material. First, we must establish the separation limits. As an upper limit, we adopt 12″, a somewhat arbitrary limit, which, however, is consistent with the upper limit used by Reipurth & Zinnecker (1993) in their survey of visual pre–main-sequence binaries in nearby clouds. The lower limit is not obvious. Our formal resolution with the A array at 3.6 cm is about 0.″2, but the detectability of a companion depends also on the flux ratio. Furthermore, the sources can be extended because of thermal radio jets. As an example, we did not detect at 3.6 cm the binary in IRAS 04368+2557 in L1527, which Loinard et al. (2002) resolved into two components separated by about 0.″2 at 7 mm, also with the A array. On the other hand, we resolved very well the L1551NE binary, which has a separation of 0.″5, despite both sources being extended themselves (see Fig. 8 of Paper II). We thus feel confident that we can detect binaries with separations down to at least 0.″5.

In determining the binary frequency in this separation range, we must additionally keep in mind that radio continuum sources can be variable, an example is the source OMC2/3 VLA 18, which was detected only on one of the three days it was observed. Altogether, we stress that despite the excellent spatial resolution of 3.6 cm VLA A array observations, the binary frequency we determine is clearly a lower limit, even within the chosen separation range.

In Table 4 we are listing all of the radio continuum sources from Papers I, II, and III, which are either extended or are detected also at another wavelength (near-infrared, far-infrared, and/or submillimeter). We believe that this restriction provides us with a clean sample of very young embedded sources. We considered including variability as a signature of youth but feel that so little is still known about this property that it is premature to use. We furthermore exclude the sources in NGC 2264, which at a distance of 800 pc is almost twice as far as the Orion sources. Altogether, 21 sources are listed in Table 4. Among these, seven are observed to have companions within 12″, corresponding to 33% of the sample. However, we have additional but indirect evidence for binarity by examining the structure of extended radio jets (Reynolds 1986; Rodríguez 1997). For example, the radio jet from IRAS 04368+2557 in L1527 shows significant curvature, suggesting that the driving source is a close binary, as confirmed by Loinard et al. (2002). Two more sources, NGC 1333 VLA 2 and OMC2/3 VLA 4, for which we did not directly detect companions, show pronounced wiggling of their radio jets. If we include these three apparently unresolved binaries, we find a binary frequency of 48%. It is noteworthy that among the 21 sources listed in Table 4, there are three triple systems (a fourth known triple system, HH 111 IRS, is only seen as two sources with the VLA). All three triple systems appear to be nonhierarchical, defined as systems where the ratios of separations differ by less than a factor 10.

In the study of Reipurth (2000), it was found that about 80% of energy sources of giant Herbig-Haro flows were binaries. In Table 4, we list a total of seven giant Herbig-Haro flows that are known or presumed to originate in one of the sources listed. Four of those giant flow sources have companions in the radio continuum maps, corresponding to 57%. If we include the one that has a curved jet, the binary frequency becomes 71%.

It is obviously risky to draw conclusions based on the small number of sources in Table 4, but we briefly mention two possible results. First, it appears that, within the defined range of separations and keeping in mind the uncertainties and caveats listed, the binary frequency among embedded sources is comparable to or only slightly larger than the binary frequency found for visual T Tauri binaries in essentially the same separation range by Reipurth & Zinnecker (1993). Second, it appears that the binary frequency for sources driving giant Herbig-Haro flows may be higher than for other embedded sources. If indeed this is so, it would be consistent with the postulate by Reipurth (2000) that giant Herbig-Haro flows are generated by dynamical interactions in small disintegrating multiple systems of newborn stars. In this view,

TABLE 4

Properties of Observed Young Sources[a]

Object	Binary?[b]	Resolved?	Curved Jet?[c]	Giant Herbig-Haro Flow[d]	Paper[e]
HH 111 IRS	Yes	Yes	No	HH 111	I
L1448 A/B	Yes	Yes	No	. . .	II
L1448 NW	No	No	No	. . .	II
NGC 1333 I2A	No	No	No	. . .	II
NGC 1333 I2B	No	No	No	. . .	II
NGC 1333 VLA2	No	Yes	Yes	. . .	II
NGC 1333 I4A1/2	Yes	No	No	. . .	II
NGC 1333 I4B	No	No	No	. . .	II
NGC 1333 I4C	No	No	No	. . .	II
L1551 NE	Yes	Yes	No	HH 28/29	II
SSV 63 E/W/NE	Yes	No	No	HH 24	II
HH 24 MMS	No	No	No	. . .	II
B335 IRS	No	Yes	No	. . .	II
Haro 6-10 VLA 1/2	Yes	Yes	No	HH 410	III
L1527 VLA 1	No	Yes	Yes	. . .	III
OMC2/3 VLA 4	No	Yes	Yes	HH 41/42	III
NGC 2023 MM VLA 1	No	No	No	. . .	III
HH 108 VLA 1	No	Yes	No	. . .	III
L1228 VLA 1	No	No	No	HH 199	III
L1228 VLA 4	No	No	No	HH 200	III
L1251 VLA 6/7/10	Yes	Yes	No	. . .	III

[a] Only objects that are extended, or are observed also at other wavelengths, and are closer than 460 pc (Orion), are included in this table.

[b] An object is considered a binary if it has a companion with a separation less than 12″.

[c] Curved jets are those that show evidence of bending or of precession, indicating that the source may be a binary.

[d] Giant jets are flows with a total projected extent of at least 1 pc.

[e] Paper I is Reipurth et al. (1999b), Paper II is Reipurth et al. (2002), and Paper III is the current study.

newborn *single* stars do not form giant Herbig-Haro flows (although they may form much smaller Herbig-Haro flows due to disk instabilities).

The extremely high resolution and ability to penetrate heavily extincted regions offered by 3.6 cm VLA observations allows a critical examination of outflow activity from the embedded sources. Outflows are detected in the radio continuum mostly as free-free emission from thermal radio jets, although in a few exceptional cases nonthermal jets have been found (e.g., Curiel et al. 1993; Wilner, Reid, & Menten 1999). In almost all cases, the free-free emission decays rapidly as the gas flows away from the driving sources, so thermal radio jets in general have very small extents. Out of the 59 sources we detected, 17 are resolved on subarcsecond scales, corresponding to 29% of the sources showing outflow activity. Since not all detected sources may be young, this percentage is a lower limit. In the sample of 21 young, nearby sources listed in Table 4, 10 are resolved (or have at least one resolved component), indicating that 48% of these sources have radio jets. We conclude that almost half of embedded sources show evidence for mass loss resulting in extended radio jets.

5. CONCLUSIONS

We have performed a deep 3.6 cm radio continuum survey of embedded protostars using the VLA in its A configuration. We mapped eight outflow regions and have combined these results with similar previously obtained maps of eight other such regions. The following results were obtained:

1. Of the 16 outflow regions, only one region contains a single source, the other regions contain an average of 3.9 sources, most of which are likely to be young. Isolated star formation is rare.

2. In order to estimate the binary frequency, we have extracted a list of 21 sources, which are either extended or have counterparts at other wavelengths and are located within 460 pc. Within the range $0\farcs5$–$12''$, seven of these sources have companions, corresponding to 33%. This is comparable to the binary frequency in the same separation range among visible T Tauri stars. An additional three sources show jets with curvature, suggesting the influence of a companion too close to be resolved. If these unresolved binaries are included, the binary frequency rises to 48%.

Among our sample of 21 young sources, seven are driving giant Herbig-Haro flows. Of these, four have companions, corresponding to an observed binary frequency of 57%. Another of these sources has a curved radio jet, and if this implies that the source is an unresolved binary, then the binary frequency increases to 71%. This is comparable to the about 80% binary frequency found in a multiwavelength study of giant Herbig-Haro flow sources by Reipurth (2000).

Among the 59 detected sources, 17 show evidence for resolved structure on subarcsecond scales, presumably due to thermal radio jets. Since some of the 59 sources may be background sources, this implies a lower limit to the number of extended outflows of 29%. In our sample of 21 young sources, 10 are resolved, corresponding to a frequency of radio jets of 48% among embedded protostars.

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REFERENCES

Allen, D. A. 1972, ApJ, 172, L55

Anglada, G. 1995, Circumstellar Disks, Outflows, and Star Formation, ed. S. Lizano & J. M. Torrelles (Rev. Mexicana Astron. Astrofis. Ser. Con. 1) (Mexico, D. F.: Inst. Astron., Univ. Nac. Autónoma México), 67

———. 1996, ASP Conf. Ser. 93, Radio Emission from the Stars and the Sun, ed. A. R. Taylor & J. M. Paredes (San Francisco: ASP), 3

Anglada, G., Rodríguez, L. F., Cantó, J., Estalella, R., & Torrelles, J. M. 1992, ApJ, 395, 494

Anglada, G., Rodríguez, L. F., Torrelles, J. M., Estalella, R., Ho, P. T. P., Cantó, J., López, R., & Verdes-Montenegro, L. 1989, ApJ, 341, 208

Anglada, G., Sepulveda, I., & Gomez, J. F. 1997, A&AS, 121, 255

Anglada, G., Villuendas, E., Estalella, R., Beltrán, M. T., Rodríguez L. F., Torrelles, J. M., & Curiel, S. 1998, AJ, 116, 2953

Balazs, L. G., Eislöffel, J., Holl, A., Kelemen, J., & Kun, M. 1992, A&A, 255, 281

Bally, J., Devine, D., Fesen, R. A., & Lane, A. P. 1995, ApJ, 454, 345

Beltrán, M. T., Estalella, R., Anglada, G., Rodríguez, L. F., & Torrelles, J. M. 2001, AJ, 121, 1556

Chini, R., Reipurth, B., Sievers, A., Ward-Thompson, D., Haslam, C. G. T., Kreysa, E., & Lemke, R. 1997, A&A, 325, 542

Chini, R., Ward-Thompson, D., Kirk, J. M., Nielbock, M., Reipurth, B., & Sievers, A. 2001, A&A, 369, 155

Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693

Cornwell, T. J., & Evans, K. F. 1985, A&A, 143, 77

Curiel, S., Rodríguez, L. F., Moran, J. M., & Cantó, J. 1993, ApJ, 415, 191

Delgado-Donate, E. J., Clarke, C. J., & Bate, M. R. 2003, MNRAS, 342, 926

DePoy, D. L., Lada, E. A., Gatley, I., & Probst, R. 1990, ApJ, 356, L55

Devine, D., Reipurth, B., Bally, J., & Balonek, T. J. 1999, AJ, 117, 2931

Gómez, M., Whitney, B. A., & Kenyon, S. J. 1997, AJ, 114, 1138

Goodrich, R. W. 1986, AJ, 92, 885

Gregersen, E. M., Evans II, N. J., Mardones, D., & Myers, P. C. 2000, ApJ, 533, 440

Haikala, L. K., & Laureijs, R. J. 1989, A&A, 223, 287

Haro, G. 1953, ApJ, 117, 73

Haro, G., Iriarte, B., & Chavira, E. 1953, Bol. Obs. Tonantzintla Tacubaya, 8, 3

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

Koresko, C. D., Herbst, T. M., & Leinert, Ch. 1997, ApJ, 480, 741

Kun, M. 1998, ApJS, 115, 59

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

Launhardt, R., Mezger, P. G., Haslam, C. G. T., Kreysa, E., Lemke, R., Sievers, A., & Zylka, R. 1996, A&A, 312, 569

Leinert, Ch., Beck, T. L., Ligori, S., Simon, M., Woitas, J., & Howell, R. R. 2001, A&A, 369, 215

Leinert, Ch., & Haas, M. 1989, ApJ, 342, L39

Loinard, L., Rodríguez, L. F., D'Alessio, P., Wilner, D. J., & Ho, P. T. P. 2002, ApJ, 581, L109

Malin, D. F., Ogura, K., & Walsh, J. R. 1987, MNRAS, 227, 361

Margulis, M., Lada, C. J., & Snell, R. L. 1988, ApJ, 333, 316

Meehan, L. S., Wilking, B. A., Claussen, M. J., Mundy, L. G., & Wootten, A. 1998, AJ, 115, 1599

Ménard, F., Monin, J.-L., Angelucci, F., & Rouan, D. 1993, ApJ, 414, L117

Morata, O., Estalella, R., López, R., & Planesas, P. 1997, MNRAS, 292, 120

Movsessian, T. A., & Magakian, T. Yu. 1999, A&A, 347, 266

Nakano, M., Sugitani, K., & Morita, K. 2003, PASJ, 55, 1

Ogura, K., & Sato, F. 1990, PASJ, 42, 583

Reipurth, B. 2000, AJ, 120, 3177

Reipurth, B., & Aspin, C. 1997, AJ, 114, 2700

Reipurth, B., Bally, J., & Devine, D. 1997, AJ, 114, 2708

Reipurth, B., & Eiroa, C. 1992, A&A, 256, L1

Reipurth, B., Rodríguez, L. F., Anglada, G., & Bally, J. 2002, AJ, 124, 1045 (Paper II)

Reipurth, B., Rodríguez, L. F., & Chini, R. 1999a, AJ, 118, 983

Reipurth, B., Yu, K. C., Heathcote, S., & Bally, J. 2000, AJ, 120, 1449

Reipurth, B., Yu, K. C., Rodríguez, L. F., Heathcote, S., & Bally, J. 1999b, A&A, 352, L83 (Paper I)

Reipurth, B., & Zinnecker, H. 1993, A&A, 278, 81

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

Rodríguez, L. F. 1997, in IAU Symp. 182, Herbig-Haro Flows and the Birth of Low Mass Stars, ed. B. Reipurth & C. Bertout (Dordrecht: Kluwer), 83

Rodríguez, L. F., et al. 1998, Nature, 395, 355

Rodríguez, L. F., & Reipurth, B. 1994, A&A, 281, 882

———. 1996, Rev. Mexicana Astron. Astrofis., 32, 27

———. 1998, Rev. Mexicana Astron. Astrofis., 34, 13

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

Sandell, G., et al. 1999, ApJ, 519, 236

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

Sato, F., Mizuno, A., Nagahama, T., Onishi, T., Yonekura, Y., & Fukui, Y. 1994, ApJ, 435, 279

Schreyer, K., Helmich, F. P., van Dishoeck, E. F., & Henning, T. 1997, A&A, 326, 347

Schwartz, P. R., Gee, G., & Huang, Y.-L. 1988, ApJ, 327, 350

Siebenmorgen, R., & Krügel, E. 2000, A&A, 364, 625

Tafalla, M., & Myers, P. C. 1997, ApJ, 491, 653

Tamura, M., Ohashi, N., Hirano, N., Itoh, Y., & Moriarty-Schieven, G. H. 1996, AJ, 112, 2076

Thompson, R. I., Corbin, M. R., Young, E., & Schneider, G. 1998, ApJ, 492, L177

Thompson, R. I., & Tokunaga, A. T. 1978, ApJ, 226, 119

Tóth, L. V., & Walmsley, C. M. 1996, A&A, 311, 981

Wang, H., Yang, J., Wang, M., & Yan, J. 2002, A&A, 389, 1015

Ward-Thompson, D., Zylka, R., Mezger, P. G., & Sievers, A. 2000, A&A, 355, 1122

White, G. J., Sanderson, C., Monteiro, T. S., Richardson, K. J., & Hayashi, S. S. 1990, A&A, 227, 200

Williams, J. P., & Garland, C. A. 2002, ApJ, 568, 259

Wilner, D. J., Reid, M. J., & Menten, K. M. 1999, ApJ, 513, 775

Wolf-Chase, G. A., & Gregersen, E. 1997, ApJ, 479, L67

Wolstencroft, R. D., Scarrott, S. M., Warren-Smith, R. F., Walker, H. J., Reipurth, B., & Savage, A. 1986, MNRAS, 218, 1P

Yu, K. C., Bally, J., & Devine, D. 1997, ApJ, 485, L45

Yu, K. C., Billawala, Y., Smith, M. D., Bally, J., & Butner, H. M. 2000, AJ, 120, 1974