JVLA OBSERVATIONS OF IC 348 SW: COMPACT RADIO SOURCES AND THEIR NATURE

Luis F. Rodríguez1,2, Luis A. Zapata1, and Aina Palau1

1 Centro de Radioastronomía y Astrofísica, UNAM, Apdo. Postal 3-72 (Xangari), 58089 Morelia, Michoacán, Mexico; l.rodriguez@crya.unam.mx, l.zapata@crya.unam.mx, a.palau@crya.unam.mx

2 Astronomy Department, Faculty of Science, King Abdulaziz University, P.O. Box 80203, Jeddah 21589, Saudi Arabia

Received 2014 March 24; accepted 2014 June 8; published 2014 July 7

ABSTRACT

We present sensitive 2.1 and 3.3 cm Jansky Very Large Array radio continuum observations of the region IC 348 SW. We detect a total of 10 compact radio sources in the region, 7 of which are first reported here. One of the sources is associated with the remarkable periodic time-variable infrared source LRLL 54361, opening the possibility of monitoring this object at radio wavelengths. Four of the sources appear to be powering outflows in the region, including HH 211 and HH 797. In the case of the rotating outflow HH 797, we detect a double radio source at its center, separated by ∼3″. Two of the sources are associated with infrared stars that possibly have gyrosynchrotron emission produced in active magnetospheres. Finally, three of the sources are interpreted as background objects.

Key words: ISM: individual objects (IC 348, HH 211, HH 797) – ISM: jets and outflows – radio continuum: stars – stars: pre-main sequence

Online-only material: color figures

1. INTRODUCTION

IC 348 is a young (∼2–3 Myr) open cluster with more than 300 members identified from optical and infrared observations (Herbig 1998; Lada & Lada 1995; Preibisch 2003). Its distance is usually estimated to be that of the Perseus molecular cloud complex, ∼300 pc (Herbig 1998), although more recent maser parallax determinations to NGC 1333 and L1448 favor ∼240 pc (Hirotâ et al. 2008, 2011; see also Chen et al. 2013). The cluster extends about 15′ × 15′ in the sky, approximately centered on the B5V star BD +31° 643, the most massive and optically brightest member of the cluster. The southwest part of the cluster (which we refer to as IC 348 SW) is particularly interesting because it hosts two highly collimated Herbig–Haro (HH) outflows: HH 211 and HH 797.

HH 797 is one of the best cases of an apparently rotating molecular outflow (Pech et al. 2012). These are systems that present a velocity gradient perpendicular to the flow axis. This gradient has been interpreted as produced by rotation in the present a velocity gradient perpendicular to the flow axis. This excited sources of outflows are usually detected as weak free–free emission produced in active magnetospheres. Finally, three of the sources are interpreted as background objects.

2. OBSERVATIONS

The observations were made with the Karl G. JVLA of NRAO3 centered at rest frequencies of 14.0 (2.1 cm) and 9.0 (3.3 cm) GHz during 2013 June. At that time the array was in its C configuration. The phase center was at α(2000) = 03h 43m 57s.0; δ(2000) = +32°03′04″0. For both observations, the absolute amplitude calibrator was J1337+3309 and the phase calibrator was J0336+3218.

The digital correlator of the JVLA was configured in 31 spectral windows of 128 MHz width divided in 64 channels of spectral resolution. The first 15 windows were used to observe at 2.1 cm, and the rest to observe at 3.3 cm. The total bandwidth for both observations was about 2.048 GHz in a dual-polarization mode. The half power width of the primary beam is 5.0′ at 3.3 cm and 3.2′ at 2.1 cm.

The data were analyzed in the standard manner using CASA (Common Astronomy Software Applications) package of NRAO, although for some stages of the analysis we used the AIPS (Astronomical Image Processing System) package. In both observations, we used the ROBUST parameter of CLEAN set to 2, to obtain a better sensitivity losing some angular resolution. To construct the continuum in both bands, we only used the free-line channels. At 2.1 cm, the resulting image rms was 5 μJy beam−1 at an angular resolution of 2′40 × 1′67 with P.A. = −75°2. On the other hand, at 3.3 cm, the resulting image rms was 4 μJy beam−1 at an angular resolution of 3′92 × 2′52 with P.A. = −77°5.

3. COMMENTS ON INDIVIDUAL SOURCES

The radio sources with peak flux densities above 5σ at 3.3 and 2.1 cm were considered detections and are listed in Tables 1 and 2, respectively. In Table 1, we give the JVLA number of the source, its possible association reported in the literature, its right ascension and declination, its flux density and the deconvolved dimensions of three of the sources. In Table 2, we give the JVLA number of the source, its right ascension and declination, its flux density and the derived spectral index. All sources at 2.1 cm appeared as unresolved and no deconvolved dimensions are presented in Table 2. Of the total of 10 objects reported here, only 3 (sources JVLA 2, 3b, and 5) had been reported previously as radio sources.

3.1. JVLA 1

This radio source is associated with the infrared source LRLL 54361 (Luhman et al. 1998), as can be seen in Figure 1. In this

---

3 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
### Table 1
Parameters of the JVLA Sources Detected at 3.3 cm

| Source | Name          | Position | Flux Density$^a$ | Deconvolved Size$^b$ |
|--------|---------------|----------|------------------|----------------------|
|        |               | $\alpha_{2000}$ | $\delta_{2000}$ | ($\mu$Jy)       | Maj. |
|        |               | (h m s)   | (\arcsec, \arcsec) |            | (\arcmin) | Min. | P.A. (\arcdeg) |
| JVLA 1 | LRLL 54361    | 03 43 51.043 | +32 03 07.62 | 53 ± 11 | ...    | ... | ... |
| JVLA 2 | HH 211-MM     | 03 43 56.781 | +32 00 50.77 | 186 ± 25 | ...    | ... | ... |
| JVLA 3 | HH 797-SMM2   | 03 43 56.928 | +32 03 03.10 | 47 ± 6  | 4.2 ± 1.2 | 2.2 ± 1.1 | 56 ± 38 |
| JVLA 3 | HH 797-SMM2   | 03 43 57.093 | +32 03 04.69 | 79 ± 17 | 3.4 ± 0.9 | 0.6 ± 0.4 | 77 ± 14 |
| JVLA 3 | HH 797-SMM2E  | 03 43 57.703 | +32 03 10.00 | ≤16    | ...    | ... | ... |
| JVLA 4 |               | 03 43 57.650 | +32 03 29.62 | 48 ± 11 | 2.0 ± 1.2 | 0.6 ± 0.5 | 93 ± 40 |
| JVLA 5 | IC 348 LRL 49 | 03 43 57.610 | +32 01 37.36 | 188 ± 15 | ...    | ... | ... |
| JVLA 6 | IC 348 LRL 13 | 03 43 59.632 | +32 01 54.14 | 46 ± 5  | ...    | ... | ... |
| JVLA 7 |               | 03 44 01.662 | +32 04 38.87 | 47 ± 7  | ...    | ... | ... |
| JVLA 8 |               | 03 44 02.653 | +32 02 03.79 | 32 ± 5  | ...    | ... | ... |

Notes.

$^a$ Total flux density corrected for primary beam response, obtained from the task JMFIT of AIPS. Upper limits are at the 4$\sigma$ level.

$^b$ These values were obtained from the task JMFIT of AIPS.

### Table 2
Parameters of the JVLA Sources Detected at 2.1 cm

| Source | Position | Flux Density$^a$ | Spectral Index |
|--------|----------|------------------|---------------|
|        | $\alpha_{2000}$ | $\delta_{2000}$ | ($\mu$Jy)       | |
|        | (h m s)   | (\arcsec, \arcsec) |            | |
| JVLA 1 | 03 43 51.001 | +32 03 08.16 | 49 ± 9  | −0.2 ± 0.6$^b$ |
| JVLA 2 | 03 43 56.819 | +32 00 50.10 | 210 ± 22 | +0.3 ± 0.4 |
| JVLA 3 | 03 43 56.892 | +32 03 03.21 | 65 ± 15  | +0.7 ± 0.6 |
| JVLA 3 | 03 43 57.053 | +32 03 04.64 | 104 ± 16 | +0.6 ± 0.6 |
| JVLA 3 | 03 43 57.703 | +32 03 10.00 | 27 ± 8   | ≥1.2 ± 0.9 |
| JVLA 4 | 03 43 57.073 | +32 03 29.51 | 28 ± 9   | −1.2 ± 0.9 |
| JVLA 5 | 03 43 57.619 | +32 01 37.43 | 142 ± 14 | −0.6 ± 0.3 |
| JVLA 6 | 03 43 59.647 | +32 01 54.10 | 54 ± 8   | +0.4 ± 0.4 |
| JVLA 7 | 03 44 01.662 | +32 04 38.87 | ≤20  | ≤−1.9 ± 0.7 |
| JVLA 8 | 03 44 02.653 | +32 02 03.79 | ≤20  | ≤−1.1 ± 0.7 |

Notes.

$^a$ Total flux density corrected for primary beam response, obtained from the task JMFIT of AIPS. Upper limits are at the 4$\sigma$ level.

$^b$ The spectral index was obtained assuming that the sources detected at 3.3 and 2.1 cm are the same.

This source coincides in position with the exciting source of the HH 211 molecular outflow (McCaughey et al. 1994; Gueth & Guilloteau 1999; Palau et al. 2006). It was previously detected with the VLA in 1994 (Avila et al. 2001) with a flux density of 90 ± 12 $\mu$Jy and in 2008 (Forbrich et al. 2011) with a flux density of 87 ± 22 $\mu$Jy, both observations at 3.5 cm. The flux density of 186 ± 25 $\mu$Jy found by us for the 2013 observations at 3.3 cm suggests that the source has increased its flux density by a factor of two in the period from 2008 to 2013. The free–free jets that excite outflows and HH systems are usually steady in time. However, evidence of variability has been presented for some of them (e.g., Galván-Madrid et al. 2004; Rodríguez et al. 2008). The variation detected by us is consistent with the episodic nature of the HH 211 jet, that seems to have a period of a few decades (Lee et al. 2007).

### 3.2. JVLA 2

This source is located at the center of the HH 797 outflow (McCaughey et al. 1994; Eislöffel et al. 2003) and is associated with the source IC 348-SMM2 (Walawender et al. 2006). In the radio it is a triple source (see Figure 2), with the parameters of its components a, b, and c given in Tables 1 and 2. The components a and b are well separated in the 2.1 cm observations. A single radio source, most likely the combination of components a and b, was detected by Forbrich et al. (2011). The source MMS1 (Chen et al. 2013) also overlaps the radio components a and b. The multiplicity of this source is relevant because the HH 797 outflow is known to present apparent rotating kinematics (Pech et al. 2012). A double outflow system can mimic the kinematics of a rotating outflow and our data opens the possibility that in this source the brightest radio components a and b (that are located close to the centroid of the HH 797 outflow) may be tracing independent jets that power nearly parallel, highly collimated outflows. Indeed, the 4.5 $\mu$m Spitzer image shown in Figure 1 suggests twin outflows forming the object HH 797 (see also Figure 6 in Walawender et al. 2006), although the two narrow filaments seen along the source could also be tracing the limb of a
single outflow. The positive spectral indices of components a and b (Table 2) are also consistent with a thermal jet interpretation.

The radio component 3c coincides with the millimeter source MMS2 (Chen et al. 2013), a very low-mass object powering a compact outflow recently detected by Palau et al. (2014). The spectral index of this source is consistent within the noise with optically thick thermal free–free emission or with optically thin thermal dust emission (see Palau et al. 2014 for further details).

3.4. JVLA 4, 7, and 8

These three sources lack of a counterpart at other wavelengths and their negative spectral indices suggest optically thin synchrotron sources, most likely faint background radio galaxies. Following Anglada et al. (1998), we estimate that in the region imaged in Figure 1 we expect $\sim 2$ background sources above 30 $\mu$Jy at 3.3 cm. This is consistent with the number of sources detected.

3.5. JVLA 5 and 6

These radio sources coincide positionally with the young stellar objects IC 348 LRL 49 and 13 (Luhman et al. 1998), respectively. They are also the only sources reported here that coincide with X-ray sources, CXOUJ034357.62+320137.4 (JVLA 5) and CXOUJ034359.67+320154.1 (JVLA 6), as reported in the study of Stelzer et al. (2012). JVLA 5 was detected previously at 3.5 cm with the VLA in 1994 (Avila et al. 2001), with a flux density of 480 $\pm$ 21 $\mu$Jy and in 2008 (Forbrich et al. 2011) with a flux density of 552 $\pm$ 17 $\mu$Jy. These flux densities are about three times larger than that reported here at 3.3 cm, implying
Figure 2. JVLA 2.1 cm continuum contour image overlaid in a JVLA 3.3 cm (color scale indicated by the bar on the right side of the panels) image for several sources in IC 348 SW. In the upper panel, the black contours are 20 and 37 μJy beam⁻¹, in the middle panel are from 81, 98, 116, and 125 μJy beam⁻¹, and in the lower panel are 20, 37, 54, and 87 μJy beam⁻¹. The cross in the upper panel marks the centroid position of the Spitzer/IRAC source (Muzerolle et al. 2013). The half-power contour of the synthesized beams of the 3.3 and 2.1 cm images are shown in the bottom left corner. The letter “I” in the upper right corner indicates the images are of the Stokes I parameter.

(A color version of this figure is available in the online journal.)

4. CONCLUSIONS

The high sensitivity of the Jansky VLA allows the detection of a diversity of sources in regions of star formation. The main results of our study of IC 348 SW can be summarized as follows.

1. We detected a total of 10 compact radio sources, determining their positions, flux densities, and spectral indices. Seven of these sources are new detections.

2. One of the sources (JVLA 1) is associated with the remarkable periodic time-variable infrared source LRLL 54361 (Muzerolle et al. 2013). This detection indicates that this source can be monitored also at radio wavelengths, helping to determine its nature.

3. Four of the sources (JVLA 2, 3a, 3b, and 3c) power outflows. JVLA 2 powers HH 211, while the sources JVLA 3a and 3b appear at the center of the outflow HH 797 and may explain its apparent rotation as due to the superposition of two nearly parallel outflows. JVLA 3c powers a compact outflow recently detected by Palau et al. (2014).

4. Two of the sources (JVLA 5 and 6) are associated with infrared stars and most probably are gyrosynchrotron sources, useful for future astrometric work.

5. Finally, three of the sources (JVLA 4, 7 and 8) are most likely background extragalactic sources.

We thank James Muzerolle as well as an anonymous referee for valuable comments. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. L.F.R., L.A.Z., and A.P. are grateful to CONACyT, Mexico, and DGAPA, UNAM for their financial support.

REFERENCES

Anglada, G., Villuendas, E., Estalella, R., et al. 1998, AJ, 116, 2953
Avila, R., Rodríguez, L. F., & Curiel, S. 2001, RMxAA, 37, 201
Chen, X., Arce, H. G., Zhang, Q., et al. 2013, ApJ, 768, 110
Dzib, S. A., Loinard, L., Mioduszewski, A. J., et al. 2013, ApJ, 775, 63
Eislöffel, J., Froebrich, D., Stanke, T., & McCaughrean, M. J. 2003, ApJ, 595, 259
Forbrich, J., Osten, R. A., & Wolk, S. J. 2011, ApJ, 736, 25
Galván-Madrid, R., Avila, R., & Rodríguez, L. F. 2004, RMxAA, 40, 31
Gueth, F., & Guilloteau, S. 1999, A&A, 343, 571
Herbig, G. H. 1998, ApJ, 497, 736
Hirota, T., Bushimata, T., Choi, Y. K., et al. 2008, PASJ, 60, 37
Hirota, T., Honma, M., Imai, H., et al. 2011, PASJ, 63, 1
Lada, E. A., & Lada, C. J. 1995, AJ, 109, 1682
Lee, C.-F., Ho, P. T. P., Palau, A., et al. 2007, ApJ, 670, 1188
Liu, H. B., Galván-Madrid, R., Forbrich, J., et al. 2014, ApJ, 780, 155
Loinard, L., Mioduszewski, A. J., Torres, R. M., et al. 2011, RMxAA, 40, 205
Luhman, K. L., Rieke, G. H., Lada, C. J., & Lada, E. A. 1998, ApJ, 508, 347
McCaughrean, M. J., Rayner, J. T., & Zinnecker, H. 1994, ApJL, 436, L189
Muzerolle, J., Furlan, E., Flaherty, K., & grey synochronor sources, useful for future astrometric work.

5. Finally, three of the sources (JVLA 4, 7 and 8) are most likely background extragalactic sources.

We thank James Muzerolle as well as an anonymous referee for valuable comments. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. L.F.R., L.A.Z., and A.P. are grateful to CONACyT, Mexico, and DGAPA, UNAM for their financial support.

REFERENCES

Anglada, G., Villuendas, E., Estalella, R., et al. 1998, AJ, 116, 2953
Avila, R., Rodríguez, L. F., & Curiel, S. 2001, RMxAA, 37, 201
Chen, X., Arce, H. G., Zhang, Q., et al. 2013, ApJ, 768, 110
Dzib, S. A., Loinard, L., Mioduszewski, A. J., et al. 2013, ApJ, 775, 63
Eislöffel, J., Froebrich, D., Stanke, T., & McCaughrean, M. J. 2003, ApJ, 595, 259
Forbrich, J., Osten, R. A., & Wolk, S. J. 2011, ApJ, 736, 25
Galván-Madrid, R., Avila, R., & Rodríguez, L. F. 2004, RMxAA, 40, 31
Gueth, F., & Guilloteau, S. 1999, A&A, 343, 571
Herbig, G. H. 1998, ApJ, 497, 736
Hirota, T., Bushimata, T., Choi, Y. K., et al. 2008, PASJ, 60, 37
Hirota, T., Honma, M., Imai, H., et al. 2011, PASJ, 63, 1
Lada, E. A., & Lada, C. J. 1995, AJ, 109, 1682
Lee, C.-F., Ho, P. T. P., Palau, A., et al. 2007, ApJ, 670, 1188
Liu, H. B., Galván-Madrid, R., Forbrich, J., et al. 2014, ApJ, 780, 155
Loinard, L., Mioduszewski, A. J., Torres, R. M., et al. 2011, RMxAA, 40, 205
Luhman, K. L., Rieke, G. H., Lada, C. J., & Lada, E. A. 1998, ApJ, 508, 347
McCaughrean, M. J., Rayner, J. T., & Zinnecker, H. 1994, ApJL, 436, L189
Muzerolle, J., Furlan, E., Flaherty, K., & grey synochronor sources, useful for future astrometric work.

5. Finally, three of the sources (JVLA 4, 7 and 8) are most likely background extragalactic sources.

We thank James Muzerolle as well as an anonymous referee for valuable comments. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. L.F.R., L.A.Z., and A.P. are grateful to CONACyT, Mexico, and DGAPA, UNAM for their financial support.