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RADIO MONITORING OF THE PERIODICALLY VARIABLE IR SOURCE LRLL 54361: NO DIRECT CORRELATION BETWEEN THE RADIO AND IR EMISSIONS

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ABSTRACT

LRLL 54361 is an infrared source located in the star-forming region IC 348 SW. Remarkably, its infrared luminosity increases by a factor of 10 over roughly one week every 25.34 days. To understand the origin of these remarkable periodic variations, we obtained sensitive 3.3 cm JVLA radio continuum observations of LRLL 54361 and its surroundings in six different epochs: three of them during the IR-on state and three during the IR-off state. The radio source associated with LRLL 54361 remained steady and did not show a correlation with the IR variations. We suggest that the IR is tracing the results of fast (with a timescale of days) pulsed accretion from an unseen binary companion, while the radio traces an ionized outflow with an extent of ∼100 AU that smooths out the variability over a period of the order of a year. The average flux density measured in these 2014 observations, $27 \pm 5\ \mu$Jy, is about a factor of two less than that measured about 1.5 years before, $53 \pm 11\ \mu$Jy, suggesting that variability in the radio is present, but over larger timescales than in the IR. We discuss other sources in the field, in particular two infrared/X-ray stars that show rapidly varying gyrosynchrotron emission.

Key words: ISM: individual objects: (IC 348, HH 797, LRLL 54361) – ISM: jets and outflows – radio continuum: stars – stars: pre-main sequence

1. INTRODUCTION

LRLL 54361 is an infrared source (Luhman et al. 1998) located in the star-forming region IC 348 SW. It presents a remarkable time variation, with its infrared luminosity increasing by a factor of 10 over roughly one week every 25.34 ± 0.01 days (Muzerolle et al. 2013). As part of a 3.3 cm study of the IC 348 SW region made with the Karl G. Jansky Very Large Array, Rodríguez et al. (2014) detected a source associated with LRLL 54361. The infrared variability was attributed to pulsed accretion from an unseen binary companion (Muzerolle et al. 2013). Since accretion and outflow are expected to be correlated in the current paradigm of star formation (e.g., Pech et al. 2010; Anglada et al. 2015), we believed that centimeter monitoring of this source could help to better understand the origin of the IR variability.

2. OBSERVATIONS

The six observations were made with the Karl G. Jansky Very Large Array of the National Radio Astronomy Observatory (NRAO)[6], centered at a rest frequency of 9.0 (3.3 cm) GHz during 2014 October 18 and 26, November 10 and 19, and December 3 and 16, under project 14B-251. At that time the array was in its C configuration. The phase center was at $\alpha(2000) = 03^h43^m51\overset{s}{.}03$; $\delta(2000) = +32°03'07\overset{''}{.}7$, approximately the radio position of LRLL 54361 as determined by Rodríguez et al. (2014). In all observations the absolute amplitude calibrator was J1337+3309 and the phase calibrator was J0336+3218.

[6] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

The digital correlator of the JVLA was configured in 16 spectral windows of 128 MHz width, each subdivided in 64 channels of spectral resolution of 2 MHz. The total bandwidth of the observations was about 2.048 GHz in a full-polarization mode. The half-power width of the primary beam is $\sim 5\overset{'}{.}0$ at 3.3 cm.

The data were analyzed in the standard manner using the VLA Calibration Pipeline[7], which uses the CASA (Common Astronomy Software Applications) package of NRAO, although for some stages of the analysis we used the AIPS (Astronomical Image Processing System) package. For all the imaging, we used the ROBUST parameter of CLEAN set to 2 (Briggs 1995), to obtain a better sensitivity, at the expense of losing some angular resolution. All images were corrected for the response of the primary beam, increasing the noise away from the phase center. The resulting rms of the averaged image (over all six epochs) was $3\ \mu\text{Jy beam}^{-1}$ at the center of the field, with an angular resolution of $3\overset{''}{.}1 \times 2\overset{''}{.}7$ with PA $= -69°$. In Table 1 we give the positions, flux densities, and deconvolved sizes of the sources detected, as obtained from the average image. With the exception of sources JVLA 3a, JVLA 3b, and JVLA 4, which show marginal evidence of being slightly extended (see Table 1), all other sources appear to be unresolved. The rms of the individual images at the center of the field was $\sim 7\ \mu\text{Jy beam}^{-1}$.

3. COMMENTS ON INDIVIDUAL SOURCES

3.1. *JVLA 5 and JVLA 6: Two Rapidly Variable Gyrosynchrotron Sources*

The only two sources that are clearly detected in the individual images at some epochs are JVLA 5 (infrared source

[7] http://science.nrao.edu/facilities/vla/data-processing/pipeline

Table 1
Parameters of the JVLA Sources Detected at 3.3 cm in the Averaged Image

Source	Name	Position α_{2000} (h m s)	Position δ_{2000} (° ′ ″)	Flux Density[a] (μJy)	Deconvolved size[b] Maj. (″)	Min. (″)	P.A. (°)
JVLA 9	…	03 43 42.094	+32 02 25.29	35 ± 6	…	…	…
JVLA 10	IC 348 3	03 43 50.998	+32 03 24.16	18 ± 3	…	…	…
JVLA 1	LRLL 54361	03 43 51.007	+32 03 08.02	27 ± 5	…	…	…
JVLA 2	HH 211-MM	03 43 56.790	+32 00 50.19	92 ± 6	…	…	…
JVLA 3a	HH 797-SMM2	03 43 56.887	+32 03 03.10	62 ± 14	2.7 ± 1.7	⩽3.9	88 ± 39
JVLA 3b	HH 797-SMM2	03 43 57.064	+32 03 05.08	37 ± 12	⩽2.8	⩽2.7	89 ± 26
JVLA 3c	IC 348-SMM2E	03 43 57.740	+32 03 10.37	23 ± 4	…	…	…
JVLA 4	…	03 43 57.088	+32 03 29.78	72 ± 19	4.2 ± 1.7	⩽3.0	130 ± 31
JVLA 5	IC 348 LRL 49	03 43 57.604	+32 01 37.37	187 ± 6	…	…	…
JVLA 6	IC 348 LRL 13	03 43 59.651	+32 01 54.07	101 ± 6	…	…	…
JVLA 7	…	03 44 01.640	+32 04 39.72	58 ± 10	…	…	…

Notes.
[a] Total flux density corrected for primary beam response. Upper limits are at the 4σ level.
[b] These values were obtained from the task JMFIT of AIPS.

IC 348 LRL 49) and JVLA 6 (infrared source IC 348 LRL 13), both of which have been detected before. We follow the nomenclature of Rodríguez et al. (2014) for the VLA sources. In Table 2 we show the flux densities of these two sources at each epoch of observation, which are seen to vary over an order of magnitude on timescales of days. In Figure 1 we show the contour image of these two sources, from the data averaged over the six epochs. These two stars are the only objects reported here that coincide with *Chandra* X-ray sources, CXOUJ034357.62+320137.4 (JVLA 5) and CXOUJ034359.67+320154.1 (JVLA 6), as reported in the work of Stelzer et al. (2012). They are also two out of four sources in this region that were detected simultaneously in X-ray and radio emission by Forbrich et al. (2011). Our results support the interpretation of Rodríguez et al. (2014) that these two radio sources are associated with young stars with active magnetospheres, such as those detected in other regions of star formation (e.g., Dzib et al. 2013; Liu et al. 2014). This class of extremely compact radio sources has been very useful for the accurate determination of the parallax (and distance) to several regions of star formation (e.g., Loinard et al. 2011).

3.2. JVLA 1 (=LRLL 54361) and JVLA 10

JVLA 1 is the radio counterpart to the variable IR source LRLL 54361 and the main target of the observations reported here. It is associated with a jet-like feature to its NW that is seen in narrowband H_2 (2.12 μm; Walawender et al. 2006) and 1.6 μm continuum (Muzerolle et al. 2013) imaging. An elongated structure is also seen to the NE in these infrared images. In a combined X-ray and cm radio study of the region, Forbrich et al. (2011) did not find evidence for either an X-ray or a radio source toward LRLL 54361 using *Chandra* and the "classic" NRAO VLA on 2008 March 13 and 18. The radio sensitivity was 20 μJy (5σ) per epoch in both the *X*- and *C*-bands. Coincidentally, the first of these observations falls onto a peak of an infrared pulse in an epoch that was observed with *Spitzer*. However, in JVLA observations in the C configuration carried out in 2013 June, Rodríguez et al. (2014) detected the source with a total flux density of 53.3 ± 3.1 μJy (at 9.0 GHz) and a flat spectral index of $\alpha = -0.3 \pm 0.2$ (with observations at 9 and 14 GHz). At the same flux level, the source thus should

Table 2
Flux Densities[a] at 3.3 cm of the Two Time Variable Sources

Epoch	LRL 49 (μJy)	LRL 13 (μJy)
2014 Oct 18	116 ± 10	44 ± 11
2014 Oct 26	234 ± 11	⩽48
2014 Nov 10	971 ± 11	112 ± 13
2014 Nov 19	118 ± 12	266 ± 13
2014 Dec 03	142 ± 12	⩽39
2014 Dec 16	39 ± 9	56 ± 13

Note.
[a] Total flux density corrected for primary beam response. Upper limits are at the 4σ level.

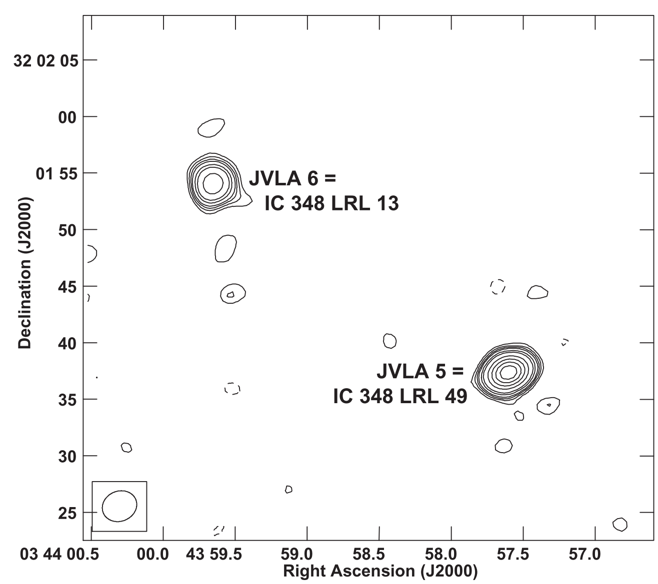

Figure 1. JVLA 3.3 cm continuum contour image of JVLA 5 and JVLA 6. The contours are −4, −3, 3, 4, 5, 6, 8, 10, 15, 20, 25, 30, and 35 times 5.4 μJy beam^{-1}, the rms noise of this region of the image. The image has been corrected for the response of the primary beam and the noise increases away from the phase center. The half-power contour of the synthesized beam is shown in the bottom left corner.

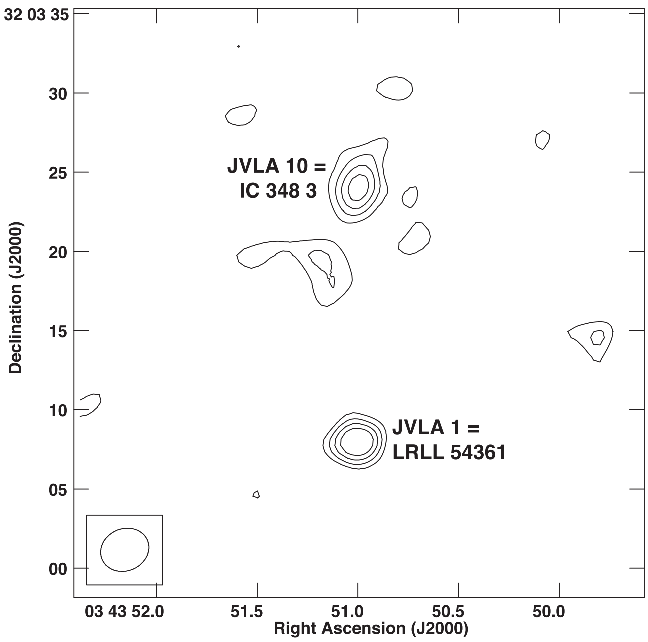

Figure 2. JVLA 3.3 cm continuum contour image of JVLA 1 and JVLA 10. The contours are −4, −3, 3, 4, 5, and 6 times 3.6 μJy beam^{-1}, the rms noise of this region of the image. The image has been corrected for the response of the primary beam and the noise increases away from the phase center. The half-power contour of the synthesized beam is shown in the bottom left corner.

have been clearly detected in 2008 at S/N $\sim$ 13, suggesting variability. The 2013 observations were carried out about 2 days after a pulse peak. The relation of the radio flux density and the phase of the infrared pulse variability was therefore inconclusive, and we carried out targeted on-peak and off-peak observations.

In our average image including all six new epochs (see Figure 2), LRLL 54361 has a 3.3 cm flux density of 27 $\pm$ 4 μJy, about one-half of the value given from the 2013 observations of Rodríguez et al. (2014), 53 $\pm$ 11 μJy. We searched for evidence of a direct correlation with the IR variability by making one image with the three IR-on epochs (2015 October 18, November 14, and December 03) and another with the three IR-off epochs (2015 October 26, November 10, and December 16). We obtain similar flux densities in these two averaged images, 23 $\pm$ 5 μJy for the IR-on epochs and 27 $\pm$ 5 μJy for the IR-off epochs. The VLA observations of Forbrich et al. (2011) were taken on 2008 March 13 and 18, with the latter epoch coinciding with an IR peak. The upper limits at the position of LRLL 54361 in the concatenated data at the *X*- and *C*-bands were on the order of 0.08 mJy (5-σ). We conclude that there is no direct correlation between the radio and IR emissions of this source. Finally, this source has no reported X-ray counterpart in the observations of Stelzer et al. (2012).

One possible explanation for this lack of correlation between the IR and radio emissions could be attributed to the timescale of the variations. The IR emission is probably tracing phenomena that take place in the accretion disk close to the central star. Given the IR variability observed, the timescale of these phenomena must be a few days or less. On the other hand, a power-law fit to the model of Muzerolle et al. (2013) for the expected dust flux density near maximum emission at millimeter and centimeter wavelengths gives

$$\left[\frac{S_\nu}{\mu Jy}\right] \simeq 3.5\left[\frac{\nu}{10\ \mathrm{GHz}}\right]^{2.9}.$$

We then expect a flux density from the dust of $\sim$3 μJy at 9 GHz. Since we observe a flux density that is an order of magnitude larger ($\sim$27 μJy), we propose that the "excess" centimeter continuum emission is probably tracing an ionized jet, as observed in several other sources (e.g., Rodríguez et al. 1998). These jets have typical detectable dimensions on the order of $\sim$100 AU (Anglada et al. 2015). Assuming a jet velocity of order 200 km s^{-1}, this outflow is averaging the ejections over a timescale on the order of one year and smoothing out possible faster variations directly associated with the IR variability. The lack of fast, significant radio variability in JVLA 1 also argues against an explanation in terms of gyrosynchrotron emission from active magnetospheres (e.g., Torres et al. 2012) or synchrotron emission from colliding magnetospheres (Salter et al. 2010) for the centimeter source.

A lack of correlation between the infrared and radio variable emissions has also been observed for other types of objects. Recently, the infrared source HOPS 383 was reported to have a mid-infrared—and bolometric—luminosity increase of a factor of 35 between 2004 and 2008 (Safron et al. 2015), becoming the first clear example of a class 0 protostar with a large accretion burst. However, Galván-Madrid et al. (2015) showed that in the time period between 1998 and 2014 the 3.0 cm flux density of the source varied only mildly, staying at a level between 200 and 300 μJy. These authors interpret the absence of a radio burst as implying that accretion and ejection enhancements do not follow each other in time, at least not within timescales shorter than a few years.

JVLA 10 is a new detection (see Figure 2). It coincides within 1″ with LRLL 54362 and appears to be located about 16″ to the north of JVLA 1 (=LRLL 54361). JVLA 10 is also associated with the young stellar object IC 348 3 (Evans et al. 2009; Gutermuth et al. 2009). In the *Spitzer* IRAC 4.5 μm image shown in Figure 1 of Rodríguez et al. (2014) JVLA 10 appears to be associated with the head of an infrared cometary nebula to its north. This cone-shaped nebula is clearly seen in the *HST* images analyzed by Muzerolle et al. (2013), but is not shown in their paper.

3.3. The Core of the HH 797 Outflow

In this zone we detect the same sources reported by Rodríguez et al. (2014). JVLA 3a and JVLA 3b are two sources separated by $\sim$3″ (see Figure 3) and located at the center of the HH 797 bipolar outflow (Pech et al. 2012). While in the observations of Rodríguez et al. (2014) the source JVLA 3b was brighter than the source JVLA 3a, the roles have reversed in these new observations, indicating variability on timescales of one year. JVLA 3a has LRLL 57025 as its K (2.2 μm) band counterpart.

JVLA 3c is an interesting source associated with the submillimeter source IC 348-SMM2E and with a Class 0 proto-brown dwarf candidate (Palau et al. 2014). Combining the 14.0 GHz observations of Rodríguez et al. (2014) with those at 9.0 GHz reported here, we derive a spectral index of 0.4 $\pm$ 0.8 for IC 348-SMM2E, consistent with a thermal jet nature, but unfortunately the large uncertainty prevents a more definitive characterization. Faint centimeter continuum

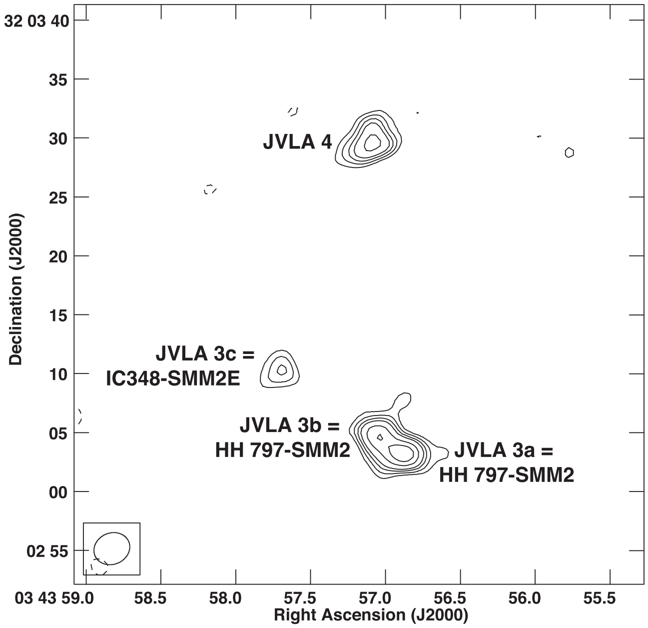

Figure 3. JVLA 3.3 cm continuum contour image of JVLA 3 and JVLA 4, at the core of the HH 797 outflow. The contours are −4, −3, 3, 4, 5, 6, 8, and 10 times 4.2 μJy beam^{-1}, the rms noise of this region of the image. The image has been corrected for the response of the primary beam and the noise increases away from the phase center. The half-power contour of the synthesized beam is shown in the bottom left corner.

emission has been reported for a handful of other proto-brown dwarf candidates (Morata et al. 2015).

The nature of JVLA 4 remains undetermined. Except for a two-band infrared detection reported as part of the c2d *Spitzer* final data release (Evans et al. 2003), it has no known counterpart at other wavelengths. The flux density reported here is 1.5 times larger than that measured in 2013. However, the associated errors are large and the source could just be steady.

3.4. New Sources

As discussed above, JVLA 10 is a newly detected radio source that is associated with the young stellar object IC 348 3. Another new source is JVLA 9, at the western edge of the field of view. This source has an infrared counterpart that was flagged as a candidate galaxy by Evans et al. (2003). Its detection in this experiment was favored by the fact that the phase center of these observations was ~76″ to the west of those of Rodríguez et al. (2014). By the same reason, here we did not detect source JVLA 8, probably because it is far to the east from the new phase center.

4. CONCLUSIONS

The high sensitivity of the Jansky VLA allows the detection of new, previously undetectable faint sources in regions of star formation. The main results of this new 3.3 cm study of IC 348 SW can be summarized as follows.

1. We detected a total of 11 compact radio sources, determining their positions and flux densities. Only two are new detections.
2. The source JVLA 1 is associated with the remarkable periodic time-variable infrared source LRLL 54361 (Muzerolle et al. 2013). Our monitoring of the region in six epochs shows no correlation between the radio and IR emissions. We suggest that the radio emission is probably tracing outflow phenomena that are averaged over timescales of years and cannot detect the rapid variability found in the IR.
3. A determination of the radio spectral index of the proto-brown dwarf IIC348-SMM2E is consistent with a thermal jet nature.
4. As proposed previously, two of the sources (JVLA 5 and 6) are each associated with infrared/X-ray young stars and are probably gyrosynchrotron emitters, useful for future high-accuracy astrometric work.

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