ON THE EVOLUTIONARY STATE OF THE COMPONENTS OF THE YLW 15 BINARY SYSTEM

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ABSTRACT

We report centimeter continuum observations with the Very Large Array (VLA) and the Very Long Baseline Array (VLBA), as well as mid-infrared observations with the Cooled Mid-Infrared Camera and Spectrometer on the Subaru Telescope toward the components of the YLW 15 very young binary system, VLA 1 and VLA 2. The centimeter emission of the two components traces partially thick free-free emission, likely due to collimated, ionized winds. VLA 1 is an embedded protostar, undetected in the near-IR, and possibly in the Class 0 to Class I transition and powering a Herbig-Haro outflow. Its mid-IR emission appears slightly resolved with a diameter of ~16 AU, possibly tracing circumstellar material from both the envelope and the disk. VLA 2 is a typical Class I object, unresolved in the mid-IR, and is responsible for the strong X-ray emission associated with YLW 15. The expected centimeter “peristellar” emission associated with the X-ray emission is not detected with the VLBA at 6 cm, likely because of the high optical depth of the free-free emission. Strikingly, the near- to mid-IR properties of YLW 15 suggest that VLA 1 is a more embedded young stellar object (YSO), or alternatively, less luminous than VLA 2, whereas orbital proper motions of this binary system indicate that VLA 1 is more massive than VLA 2. This result is apparently against the expected evolutionary scenario, in which one expects that the more massive YSO in a binary system is the more evolved and luminous YSO. Finally, the nearby source YLW 16A is detected with the VLA; its position coincides with reported near-IR and X-ray sources.

Key words: ISM: jets and outflows — stars: formation — stars: individual (YLW 15, YLW 16A)

1. INTRODUCTION

The ρ Ophiuchi molecular cloud complex is one of the nearest star formation regions (~120 pc; Knude & Høg 1998) and is also one of the best-studied low-mass star-forming regions. YLW 15 (IRS 43) is a young stellar object (YSO) embedded in the Oph-F dense core, located in the southeastern region of the molecular cloud complex (e.g., Motte, André, & Neri 1998). The near-IR to mid-IR (e.g., Wilking, Lada, & Young 1989), far-IR (e.g., Bontemps et al. 2001; Pezzuto et al. 2002; Nisini, Gianni, & Lorenzetti 2002), and millimeter (e.g., André & Montmerle 1994; Bontemps et al. 1996) properties suggest that YLW 15 belongs to the Class I stage of evolution. The spectroscopic features in the near-IR show that YLW 15 is a YSO with K5 spectral type and with dwarflike surface gravity, i.e., a luminosity class IV/V, having a stellar mass of 0.5 M⊙ (Greene & Lada 2002). It has been proposed that YLW 15 constitutes a wide binary system with GY 263, located 6″ (720 AU) northwest of YLW 15 (e.g., Allen et al. 2002). YLW 15 powers a compact molecular outflow (Bontemps et al. 1996) and a Herbig-Haro outflow (e.g., Grosso et al. 2001).

YLW 15 is one of the youngest low-mass stars associated with X-ray emission. First detected by ROSAT (Casanova et al. 1995), the X-ray emission shows quasi-periodic flares (Tsuboi et al. 2000). A “superflare” was observed during a few hours (Grosso et al. 1997). Grosso et al. (1997) suggested that the flare arises from a magnetically confined, low-density plasma bubble with a diameter of ~0.05–0.3 AU around the young star. The quasi-periodic X-ray flares of YLW 15 were explained by Montmerle et al. (2000) as due to “fast rotation of the central star with respect to the inner accretion disk, which results in star-disk shearing of the magnetic field lines, producing magnetic reconnection and mass loss, and eventually extremely high X-ray luminosities,” which is different from the “classical” quasi–steady state situation expected for the T Tauri stars.

Its radio continuum emission has been well studied at a moderate angular resolution (~10″), showing no variability (e.g., Leous et al. 1991). VLBI milliarcsecond angular resolution observations of YLW 15 show that the emission is resolved out at “peristellar” scales (i.e., its size is larger than 1.2 × 1013 cm), suggesting that the emission is thermal in origin and probably comes from circumstellar ionized winds (André et al. 1992). Subarcsecond angular resolution Very Large Array (VLA) observations revealed that the radio emission arises from a binary system, YLW 15 VLA 1 and VLA 2 (Girart, Rodríguez, & Curiel 2000, hereafter Paper I). In these maps, VLA 1 was clearly elongated with a position angle of P.A. = 25° ± 2°. This elongation aligns well with HH 224 NW 1 and a chain of near-IR HH knots (Grosso et al. 2001). VLA 2 appeared unresolved down to scales of ~0″4. In Paper I, we suggested that the two radio sources trace a binary young stellar system with each component possibly having a different evolutionary status. Using a 12 yr time baseline of subarcsecond angular resolution VLA observations, Curiel et al. (2003, hereafter Paper II) have measured absolute proper motions of 24 mas yr−1 in YLW 15. In addition, the VLA 1 and VLA 2 relative astrometry analysis done in Paper II...
reveals orbital proper motions that suggest a total mass of the binary system \( \geq 1.7 M_\odot \). These results show also that VLA 1 is likely more massive than VLA 2.

In this paper, we present VLA subarcsecond angular resolution observations at 3.6 and 6 cm toward YLW 15, as well as Very Long Baseline Array (VLBA) 6 cm and Cooled Mid-Infrared Camera and Spectrometer (COMICS) Subaru 8.8 \( \mu \)m observations. In \S 2 and 3, we give the details of the observations and results with the VLA, VLBA, and Subaru. In \S 4, we discuss the nature of the radio emission and compare its properties with those obtained at other wavelengths in order to elucidate the nature of this interesting binary protostellar system.

2. OBSERVATIONS

2.1. VLA

The subarcsecond radio continuum observations were carried out with the VLA of the National Radio Astronomy Observatory (NRAO)\(^7\) between 2000 and 2002: 2000 December 27 (3.6 and 6 cm), 2002 February 10 (3.6 cm), 2002 March 5 (3.6 cm) and 2002 March 8 and 9 (6 cm). The absolute amplitude and phase calibrator were always 3C 286 and 1626 (3.6 cm) and 2002 March 8 and 9 (6 cm). The absolute amplification observations was performed using the PHOT routine within IRAF. For the 3.6 cm flux standard star) photometry an aperture of 6 pixels (0.78) was used. The flux adopted for HD 145897 at 8.8 \( \mu \)m is 7.43 Jy. For the YLW 15 photometry, an aperture radius of 4 pixels (0.52) was used. In order to estimate the total flux of YLW 15 VLA 1 and VLA 2, we first did the aperture photometry for VLA 2, which has a peak intensity about 5 times stronger than VLA 1. The flux measured for VLA 2 is 1.49 Jy at 8.8 \( \mu \)m. For VLA 1, we first suppressed the VLA 2 emission: this was done by rescaling and shifting the HD 145897 image to match it with the VLA 2 intensity and position. Second, the resulting image was subtracted from the YLW 15 image. The aperture photometry on VLA 1 was done on the YLW 15 image where VLA 2 was suppressed. The flux measured for VLA 1 is 0.356 Jy.

3. RESULTS

3.1. YLW 15

3.1.1. VLA

Figure 1 shows the 3.6 and 6 cm subarcsecond angular resolution maps of the two epochs, 2000 and 2002. Table 3 gives the positions, flux densities, and the deconvolved sizes of VLA 1 and VLA 2. VLA 1 appears elongated, in the two epochs and at the two wavelengths, in the southwest-northeast direction, with a position angle of \( \approx 30^\circ \), which is in agreement, within the uncertainties, with the previous measurements reported in Paper I. The 2002 epoch 3.6 cm map clearly shows weak emission (at 6 \( \sigma \) level) southwestern of VLA 1, i.e., in the same direction of the elongation of VLA 1, which forms an apparent one-sided lobe of VLA 1. The 2000 epoch 3.6 cm map detects radio lobe only marginally (due to the lower sensitivity). The position angle of the VLA 1 one-sided lobe is \( \approx 25^\circ \), which is similar to the elongation of VLA 1. Remarkably, nearly aligned with the major axis of VLA 1 there is a

| Epoch (yr) | Synthesized Beam (arcsec, deg) | rms Noise (\( \mu \)Jy beam\(^{-1} \)) |
|-----------|-------------------------------|----------------------|
|           | 3.6 cm | 6 cm | 3.6 cm | 6 cm |
| 2000       | 0.55 x 0.19, +27   | 0.90 x 0.33, +25 | 50 | 59 |
| 2002       | 0.40 x 0.19, +2    | 0.67 x 0.31, +10 | 17 | 26 |

\( ^7 \) NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
chain of near-IR HH knots located to the north, and HH 224 NW 1 is located to the south (Grosso et al. 2001). This coincidence lead Grosso et al. (2001) to suggest that VLA 1 is powering this HH outflow.

VLA 2 is also slightly extended, with a deconvolved size of $\sim 0.3$, or 36 AU in projection. This result is consistent with the upper limit of 0.4 obtained in Paper I. At 6 cm, this source is not well separated from VLA 1, so the deconvolved size of VLA 2 may not be very accurate. Figure 1 clearly shows that

| Epoch (yr) | Phase Calibrator | rms Noise ($\mu$Jy beam$^{-1}$) | Synthesized Beam (mas) |
|------------|------------------|---------------------------------|------------------------|
| 2001........ | J1625–2527       | 71                              | 6.1 x 2.2, -6          |
| 2002........ | J1625–2527       | 74                              | 4.9 x 1.9, -2          |

VLA 2 is associated with the near-IR source and the X-ray emission observed in this region (see § 3.1.4).

No radio emission down to 0.05 mJy (3 $\sigma$ level) is detected toward GY 263, located 6$''$ northwest of VLA 1 and VLA 2.

In order to derive the spectral index of VLA 1 and VLA 2, we first generate 3.6 cm maps using IMAGR and applying a Gaussian taper to the visibility data to obtain a synthesized beam similar to the 6 cm maps. Then, the 3.6 and 6 cm maps were convolved with a Gaussian, so the final resulting beam for the two wavelengths was the same. For the 2000 epoch, this beam was $0.90 \times 0.33$, 22$''$. For the 2002 epoch, this beam was $0.67 \times 0.32$, 10$''$. Table 4 gives the flux densities of the convolved maps and their spectral indices for the two epochs. The overall radio continuum emission of the YLW 15 region (obtained by measuring the flux within a box that included VLA 1, VLA 2, and the weak extended emission) has an spectral index of 0.5 ± 0.1 and does not show signs of flux variability at roughly a 5% level. VLA 1 and VLA 2 have both

![Fig. 1.—VLA continuum images of YLW 15 at 3.6 cm (left) and 6 cm (right), for the epochs 2000 (top) and 2002 (bottom). Contours are $-3, 3, 4, 5, 7, 9, 12, 15, 20, \ldots, 55$ times the rms noise of the images ($50 \mu$Jy beam$^{-1}$ at 3.6 cm and 59 $\mu$Jy beam$^{-1}$ at 6 cm for the 2000 epoch, 17 $\mu$Jy beam$^{-1}$ at 3.6 cm and 26 $\mu$Jy beam$^{-1}$ at 6 cm for the 2002 epoch observations). The half-power size of the synthesized beams are shown in the bottom left corner (see Table 3 for their sizes). The cross on the left panels shows the position uncertainty (K. Imanishi 2002, private communication) of the X-ray source No. 54 (Imanishi et al. 2001). The filled triangle shows the position of the near-IR 2MASS 1627269–244050 source. The dashed line shows the direction to the HH outflow associated apparently with VLA 1 (Grosso et al. 2001).]
positive spectral indices, ~0.5 and ~0.7, respectively. Because both sources have emission arising from a few tens of AU their emission is likely optically partially thick free-free.

Figure 2 shows the slices of the VLA 1 emission and spectral indices along its major axis for the 2000 and 2002 epoch. Both epochs show that VLA 1 has a spectral index at the peak of ~0.5. Interestingly, the southwestern weak lobe had in epoch 2000 a spectral index of −0.6 ± 0.3, indicating nonthermal emission, while in the 2002 epoch its spectral index raised enough to be compatible with optically thin free-free emission (~0.1 ± 0.3).

3.1.2. VLBA

No sources were detected from the two epochs of VLBA observations with an upper limit of about 0.3 mJy beam−1 (4 σ level). The parallax due to the Earth orbiting the Sun for ρ Ophiuchi is about 8.3 mas. YLW 15 has moved 5.4 and −1.4 mas in right ascension and declination, respectively, between the two VLBA observations due to the parallax. Taking also into account the spatial displacement due to the absolute proper motions of VLA 2 measured in Paper II, the total displacement of VLA 2 is 3.0 and −9.4 mas in right ascension and declination, respectively. The visibility data of the first epoch was corrected for this shift. The maps of the combined visibility data were obtained using natural weighting, which yields an rms noise of 52 μJy. No emission was detected down to 0.21 mJy beam−1 (4 σ level). The same process was done taking into account the parallax and the VLA 1 absolute proper motion. No emission was detected either. This upper limit implies that at least 84% and 64% of the radio emission of VLA 1 and VLA 2, respectively, arise from scales > 0.5 AU, which is in agreement with the VLA results that indicate that VLA 1 and VLA 2 are being partially resolved at scales of about 20 AU.

3.1.3. COMICS/Subaru

The left and right panels of Figure 3 show the image of YLW 15 and the standard HD 145897, respectively, at 8.8 μm obtained with the COMICS camera of Subaru. The two sources in YLW 15 are well separated in the image, with VLA 2 being significantly stronger than VLA 1. The separation between VLA 1 and VLA 2 is about 0′′59 with a position angle of ~147°, which is in agreement with the values obtained from the VLA observations (see Table 3 from Paper II). There is extended emission observed up to a ~8% level with respect to the peak value of the image around the two sources. It is clear from the HD 145897 image that there is also an extended “halo” at a level of 14% level due to the Subaru telescope. Therefore the extended emission up to a ~8% level in the YLW 15 image is possibly due to the Subaru PSF. In order to confirm this possibility, we deconvolved the YLW 15 image using as a PSF model the HD 145897 image masked for levels below 2% (in order to avoid the noise to contribute into the deconvolution). Three different procedures were used for the deconvolution: the Lucy algorithm from the STSDAS package of IRAF and Maximum Entropy and CLEAN, these two from the MIRIAD package. Figure 4 (left) shows the resulting image of the Maximum Entropy deconvolution: the extended emission has disappeared down to a 2% level (a similar result is also obtained with the Lucy and CLEAN algorithms). Thus, it is clear that the extended halo around YLW 15 observed in the original image was due to the Subaru PSF.

In order to check if VLA 1 and VLA 2 are resolved at 8.8 μm, we computed the radial profile of the annular averaged normalized flux of HD 145897, VLA 2 and VLA 1 (see Fig. 4, right). The half-width half-maximum (HWHM) of these profiles are 0′′143, 0′′138, and 0′′154 for HD 145897, VLA 2 and VLA 1, respectively. HD 145897 should be unresolved (its size is ~2 mas; Cohen et al. 1999). The slightly

### Table 3

| YEAR | \( \alpha (J2000.0) \) (16′′27′′\text{″}) | \( \delta (J2000.0) \) (−24′′40′′) | S\(_V\) (mJy) | Deconvolved Size (arcsec) | P.A. (deg) | S\(_V\) (mJy) | Deconvolved Size (arcsec) | P.A. (deg) |
|------|----------------------------------|---------------------------------|-------------|------------------|----------|-------------|------------------|----------|
| YLW 15 VLA 1: | | | | | | | | |
| 2000 | 26.9120 ± 0.0004 | 50.295 ± 0.013 | 1.40 ± 0.10 | 0.40(4) × 0.07(2) | 30° ± 4° | 1.41 ± 0.13 | 0.79(9) × 0.13(5) | 26° ± 3° |
| 2002 | 26.9125 ± 0.0002 | 50.331 ± 0.005 | 1.51 ± 0.04 | 0.32(1) × ≤0. 08 | 35° ± 3° | 1.38 ± 0.06 | 0.51(3) × 0.11(5) | 33° ± 3° |
| YLW 15 VLA 2: | | | | | | | | |
| 2000 | 26.9342 ± 0.0008 | 50.795 ± 0.027 | 0.78 ± 0.11 | 0.35(8) × 0.12(4) | 26° ± 12° | 0.74 ± 0.13 | 0.56(15) × ≤0. 21 | 65° ± 15° |
| 2002 | 26.9294 ± 0.0004 | 50.899 ± 0.012 | 0.64 ± 0.04 | 0.26(3) × 0.20(4) | 11° ± 30° | 0.55 ± 0.05 | 0.27(4) × ≤0. 16 | 4° ± 21° |
| YLW 16A: | | | | | | | | |
| 2002 | 28.013 ± 0.005 | 33.69 ± 0.07 | 0.55 ± 0.05 | ... | ... | 0.27 ± 0.05 | ... | ... |

* Possibly a binary source. See discussion in text.

### Table 4

| SOURCE | 3.6 cm | 6 cm |
|--------|--------|------|
| S\(_{3.6\text{cm}}\) | S\(_{6\text{cm}}\) | \( \alpha \) | S\(_{3.6\text{cm}}\) | S\(_{6\text{cm}}\) | \( \alpha \) |
| VLA 1 | 1.88 ± 0.10 | 1.38 ± 0.12 | 0.56 ± 0.18 | 1.66 ± 0.03 | 1.27 ± 0.05 | 0.48 ± 0.08 |
| VLA 2 | 0.86 ± 0.10 | 0.54 ± 0.11 | 0.88 ± 0.41 | 0.84 ± 0.04 | 0.57 ± 0.05 | 0.70 ± 0.18 |
| Whole region | 2.96 ± 0.17 | 2.30 ± 0.22 | 0.46 ± 0.20 | 2.85 ± 0.08 | 2.18 ± 0.12 | 0.48 ± 0.11 |

* Flux densities are in millijanskys.
higher width of HD 145897 with respect to VLA 2 could be due to a slightly higher seeing during the HD 145897 observations (taken 30 minutes after YLW 15). In any case, the profile of VLA 2 likely suggests that it is unresolved $[\theta_{\text{FWHM}}(\text{VLA 2}) \ll 0^\prime.28]$. Assuming that VLA 2 is unresolved and that it traces the PSF, then the deconvolved HWHM of VLA 1 can be estimated from the observed HWHM of these two sources: $(0.154^2 + 0.138^2)^{1/2} \approx 0.068$. There are two sources of uncertainties in this estimation. First, the intrinsic uncertainty due to the angular resolution and the signal-to-noise ratio (S/N) of the source: $\text{FWHM}/(\text{S/N})$ (Condon 1997). Since the S/N for VLA 1 is $\approx 20$ and the angular resolution is $\text{FWHM} \approx 0^\prime.28$, the uncertainty is $0^\prime.014$. Second, the difference in the measured size of the reference star and VLA 2 can also be accounted as source of uncertainty: $\approx 0^\prime.005$. The total uncertainty is $(0.014^2 + 0.005^2)^{1/2} \approx 0^\prime.015$. Thus, the FWHM size for VLA 1 of $0^\prime.14 \pm 0^\prime.03$ or $16 \pm 4$ AU. Finally, we note that despite the aforementioned deconvolution algorithms are not being very reliable to derive the YLW 15 sizes because of the small difference in size between VLA 2 and HD 145897, all of them produce an unresolved deconvolved object for VLA 2 (assuming that HD 145897 is a point source), whereas for VLA 1 they produce a resolved object with a FWHM size of $0^\prime.10$–$0^\prime.14$, in agreement with the previous radial profile analysis.

The slightly resolved VLA 1 mid-IR emission possibly traces matter in a nondisk three-dimensional distribution (i.e., from the envelope) that is falling onto (or perhaps is being flung off) its circumstellar disk (e.g., Chick, Pollack, & Cassen 1996; Adams, Lada, & Shu 1987). Yet, for low-inclination angles (nearly face-on) the circumstellar disk emission could also contribute to the mid-IR emission (Osorio et al. 2003; M. Osorio 2003, private communication). Indeed, CO outflow observations suggest that YLW 15 is nearly face-on (Bontemps et al. 1996). If this mid-IR emission comes partially from a circumstellar disk, then it will trace only the inner region of the disk, which is warm enough to radiate in these wavelengths. Since the infalling envelope also contributes to the mid-IR emission, the size of the mid-IR emission does not correspond with the disk size directly. However, due to tidal truncation from the companion star (located at 72 AU in projection), its true size is probably not much larger (e.g., Rodriguez et al. 1998; Loinard et al. 2002). On the other hand, the mid-IR emission of VLA 2, unresolved, arises from a significantly smaller circumstellar structure.

3.1.4. Counterparts of the VLA sources

YLW 15 is detected in the Two Micron All Sky Survey (2MASS) in the $J$ and $K$ bands and is cataloged as 2MASS 1627269–244050. The 2MASS (second incremental release)
Point Source Catalog coordinates are given in Table 5. These near-IR data were obtained on 1998 July 9 (1998.52). In order to properly compare the positions of 2MASS 1627269/C0244050 with VLA 1 and VLA 2, we corrected the positions of these two radio sources to the values expected for the 1998.52 epoch taking into account the proper motions measured in Paper II. The difference between the positions of VLA 1 and VLA 2 for the 1998.52 epoch with respect to the 2MASS position are given in Table 5. From this table, it is clear that the near-IR source is associated with VLA 2, as suggested by Greene & Lada (2002). Similarly, we compared the positions of the two VLA sources from the 2000 observations with the position of the X-ray source obtained with the Chandra satellite in 2000 (Imanishi, Koyama, & Tsuboi 2001; K. Imanishi 2002, private communication). Given the positions uncertainties, the X-ray emission is more likely associated with VLA 2.

High angular resolution, near-IR observations with Hubble Space Telescope (HST) NICMOS (Allen et al. 2002) and using lunar occultation techniques (Simon et al. 1995) show two sources that correspond to VLA 1 and VLA 2. At these two wavelengths, VLA 2 is stronger than VLA 1, which suggests that VLA 1 is an embedded object or, alternatively, is less luminous (see § 4.3).

3.2. YLW 16A

3.2.1. VLA

This source is located 78" north of YLW 15, so it is far from the phase center of the VLA observations, but still within the primary beam of the 3.6 and 6 cm maps. This source was only detected in the 2002 epoch. Because this source is weak, in order to achieve a better S/N, the maps presented here were obtained using robust weighting of 0 and 1 at 3.6 and 6 cm, respectively. Figure 5 shows the 3.6 and 6 cm maps for YLW 16A. The 3.6 cm image shows that the emission is elongated to the west of the intensity peak. Because of the low S/N, it is not clear whether this elongation is due to a one side jet lobe (as it happens in YLW 15 VLA 1), or if it is due to a binary radio source separated by ~0.3.

Because bandwidth smearing is important for YLW 16A at 3.6 cm (~0.5 in the north-south direction), only the integrated flux density was measured, using a box that included all the emission. Thus, the primary beam corrected flux density of YLW 16A is 0.43 ± 0.04 and 0.27 ± 0.05 mJy at 3.6 and 6 cm, respectively. These values imply an spectral index of the overall emission of 0.8 ± 0.4, suggesting a thermal radio jet origin.

| OBJECT             | EPOCH   | α (J2000.0)  (16") | δ (J2000.0)  (−24") | Δα (") | Δδ (") | Δα,Δδ (") |
|--------------------|---------|-------------------|-------------------|-------|-------|----------|
| 2MASS 1627269–244050... | 1998.52 | 26.944 ± 0.012   | 50.73 ± 0.13      | 0.42 ± 0.17  | 0.48 ± 0.14   | 0.18 ± 0.17  | 0.06 ± 0.16   |
| Chandra No. 54................. | 2000.28 | 26.950 ± 0.037   | 50.9 ± 0.5        | 0.5 ± 0.5   | 0.6 ± 0.5   | 0.2 ± 0.5   | 0.1 ± 0.5   |

* Here “wrt” means “with respect to.”
3.2.2. Counterparts of the VLA sources

Allen et al. (2002) detected with the HST/NICMOS3 camera two near-IR sources with their components separated by ∼0.5'' in the east-west direction. However, Allen et al. (2002) suggested that this apparent binary system is possibly tracing scattered light from the disk of a single YSO. In addition, lunar occultation observations by Simon et al. (1995) failed to detect a binary system. To compare the position of the near-IR and VLA emission, we used the position given by the 2MASS Point Source Catalog (source 2MASS 162728.0−243933). Correcting the VLA position for proper motions (as we did in § 3.1.4), the difference between the VLA and near-IR emission, ∆α = 0''.10 ± 0''.19 and ∆δ = 0''.17 ± 0''.17, implies that both wavelength trace the same source. The Chandra X-ray source No. 57 (K. Imanishi 2002, private communication) also coincides within its position uncertainty (∼0.5'') with the VLA peak emission.

4. DISCUSSION

4.1. Radio Continuum Properties

The jetlike morphology of VLA 1 (including its weak southwestern lobe) and its spectral index at centimeter wavelengths, ~0.5, suggests that this source is a thermal radio jet (e.g., Anglada 1996; Rodriguez 1997). VLA 2 has a slightly higher spectral index, ~0.7, and it is also partially resolved at similar scales as VLA 1. Yet, it does not have a clear elongation direction (see Table 3). Since VLA 1 and VLA 2 are very young stellar objects (see § 4.3) and that a significant fraction of their radio emission arises at scales of ≥1 AU (§ 3.1.1), we can assume that their 3.6 and 6 cm emission arises from collimated, ionized winds. The radio emission of these winds was modeled by Reynolds (1986), which predicts that for a wind with constant velocity, temperature and ionization, a lower spectral index implies that the collimation of the jet increases with distance to the exciting star. Thus, the radio continuum properties of the YLW 15 radio sources (VLA 1 has a lower spectral index and has a more clear jetlike morphology than VLA 2) are in agreement with the expected properties of collimated ionized winds. The higher 3.6 cm flux of VLA 1 with respect to VLA 2 implies that the momentum rate of the outflow material is higher in VLA 1 than in VLA 2. From the correlation between the molecular outflow momentum rate and the flux of the free-free emission estimated by Anglada et al. (1998), the momentum rate expected for the molecular outflow powered by VLA 1 and VLA 2 should be 5 × 10^{-5} and 2 × 10^{-5} M_{⊙} yr^{-1} km s^{-1}, respectively. On the other hand, the lack of emission for GY 263 gives an upper limit for the momentum rate of 1 × 10^{-6} M_{⊙} yr^{-1} km s^{-1}, more than an order of magnitude lower than that of VLA 2. This suggests that GY 263 is a more evolved YSO. Indeed, the near-IR to mid-IR spectral index of GY 263 is consistent with a Class II YSO (Haisch et al. 2002).

4.2. Radio Continuum and X-Ray Emissions

VLBA observations do not detect any compact emission in YLW 15 down to ~0.21 mJy beam^{-1}. Since VLA 2 is associated with X-ray emission, it is expected to have milliarcsecond radio emission. Yet, the partially extended subarcsecond free-free emission associated with VLA 2 will significantly mask emission at milliarcsecond scales: the observed angular sizes at 6 cm suggest that the radio ''photosphere'' has dimensions ≥10 AU. Any emission processes taking place at 6 cm inside this photosphere will suffer from significant free-free absorption and will be very difficult to detect. In order to avoid the absorption of the extended free-free emission, and thus to be more sensitive to milliarcsecond emission, VLBA observations would be best done at 2 cm (where the radio photosphere will be about 2 times smaller and the optical depth will also be smaller) or at shorter wavelengths.
properties of YLW 15 available in the literature. Figure 6 shows that it is clear that VLA 1 is a YSO. The properties of VLA 1 and VLA 2 (Paper II) clearly shows that these two sources are gravitationally bounded, with VLA 1 being more massive. Therefore, it is clear that VLA 1 is a YSO. The properties of VLA 1 and VLA 2 can be derived from the near-IR through far-IR properties of YLW 15 available in the literature. Figure 6 shows the $\lambda F_{\lambda}$-$\lambda$ plot for those observations in the near to mid-IR range with enough angular resolution to resolve spatially VLA 1 and VLA 2 (Allen et al. 2002; Haisch et al. 2002). It is clear from this plot that the luminosity in the near to mid-IR is clearly dominated by VLA 2. The dashed line shows the spectral energy distribution (SED) of VLA 2 scaled down, so the $\lambda F_{\lambda}$ value of the dashed line at 10.78 $\mu$m coincides with that of VLA 1.

4.3. Evolutionary Status of VLA 1 and VLA 2

Greene & Lada (2002) and Haisch et al. (2002) argue that VLA 1 and its mid-IR counterpart is not a true star but instead has an outflow origin (i.e., it could be an HH knot). However, the VLA proper motions measured in VLA 1 and VLA 2 (Paper II) clearly shows that these two sources are gravitationally bounded, with VLA 1 being more massive. Therefore, it is clear that VLA 1 is a YSO. The properties of VLA 1 and VLA 2 can be derived from the near-IR through far-IR properties of YLW 15 available in the literature. Figure 6 shows the $\lambda F_{\lambda}$-$\lambda$ plot for those observations in the near to mid-IR range with enough angular resolution to resolve spatially VLA 1 and VLA 2 (Allen et al. 2002; Haisch et al. 2002). It is clear from this plot that the luminosity in the near to mid-IR is clearly dominated by VLA 2. The dashed line shows the spectral energy distribution (SED) of VLA 2 scaled down, so the $\lambda F_{\lambda}$ value of the dashed line at 10.78 $\mu$m coincides with that of VLA 1.

The observed near-IR properties show that VLA 2 is a Class I YSO (Haisch et al. 2002; Greene & Lada 2002). In addition, the overall properties of YLW 15 from the far-IR through the millimeter wavelengths (see § 1) show they also are in agreement with those found in Class I objects. Yet, which is the evolutionary state of VLA 1? Taking into account the near-to-mid-IR SED (Fig. 6), there are two possible scenarios for VLA 1: it is more embedded than VLA 2 (i.e., with a steeper SED), or, alternatively, VLA 1 has a similar SED but a lower bolometric luminosity than VLA 2. For this later scenario, the upper limit of the VLA 1 stellar luminosity would be $3 L_{\odot}$ (the value for VLA 2: Greene & Lada 2002). In the first scenario, since the overall properties of YLW 15 are in agreement with those of Class I sources, VLA 1 cannot be much more embedded than VLA 2 (i.e., a Class 0 object). We suggest that VLA 1 is a very embedded YSO in the Class 0 to Class I transition, since it may also be L1448 IRS3(A) (Ciardi et al. 2003). In this scenario, VLA 1 probably dominates the millimeter dust emission and has a stronger outflow. Indeed, VLA 1 is the powering source of a HH system (Grosso et al. 2001) and its radio centimeter emission is stronger than in VLA 2. We speculate that being YLW 15 a binary young stellar system, the dynamical perturbation of the two YSO could diminish the circumstellar mass with respect to the expected values for isolated stars. In fact, the more evolved, Class II, T Tauri close binary stars (with separations in the 1–100 AU range) have less millimeter emission than single T Tauri stars (Jensen, Mathieu, & Fuller 1996).

A conclusive test of which of the two sources is more luminous and which is the evolutionary status of VLA 1 as well as its dust properties will come from high angular resolution observations in the millimeter and submillimeter, as those that will be achieved in the future by the SMA, CARMA, and ALMA, and at other wavelengths in the near to mid-IR range.

The most striking feature of the YLW 15 binary system is that VLA 1 appears to be a more massive and more embedded (thereby less evolved) or, alternatively, less luminous YSO than VLA 2. Interestingly, this result is apparently against the expected evolutionary scenario, where one expects that the more massive YSO in a binary system is the more evolved and luminous YSO. Simulations of the evolution of binary YSOs with circumstellar and circumbinary disks show that if one of the two YSO is less massive, the dynamical effects of the system can cause a larger accretion rate to the less massive star (that is expected to evolve more slowly), which will tend to equalize the masses (Lubow & Artymowicz 2000). However, this still does not explain that the more massive is apparently less evolved or less luminous. A plausible explanation is that the less massive component may indeed be more luminous because of its higher accretion rate, since (accretion) luminosity is proportional to accretion rate times stellar mass. GY 263, a Class II YSO and so clearly more evolved than the YLW 15 binary system, is only at 6" (720 AU in projection) from YLW 15. If it is truly so close to YLW 15, GY 263 could have had in the past a close approach to YLW 15 and altered significantly the star formation process of YLW 15, possibly reducing the accretion process to the circumbinary disk around YLW 15 (which may explain the low millimeter flux of YLW 15 and the low momentum flux of the CO outflow) and, therefore, altering somewhat the evolutionary scenario of the binary system.

5. CONCLUSIONS

We have carried out VLA and VLBA radio, as well as COMICS/Subaru mid-IR (8.8 $\mu$m) observations of the YSO binary system in YLW 15, and carried out a study of the properties of YLW 15 from previous results available in the literature. The main conclusions are as follows:

1. The properties of the radio continuum emission of VLA 1 and VLA 2 show that these two sources have partially thick
free-free emission, likely due to collimated, ionized winds, as is the case for other Class I and 0 YSOs, with associated molecular and/or HH outflows.

2. The centimeter VLA 1 emission has a jetlike morphology, with the axis coinciding in position angle with the HH outflow found by Grosso et al. (2001) and a jet length of ~0.32 or ~40 AU. Undetected in the near-IR, becomes “visible” at 8.8 μm. The 8.8 μm emission is slightly resolved, with a deconvolved size of ~16 AU, suggesting that the emission arises from a compact circumstellar structure around the protostar.

3. The centimeter VLA 2 emission is partially resolved at scales of 20 AU. Comparison with data taken at other wavelengths shows that VLA 2 is responsible for the near-IR emission, and it is the source of the strong X-ray emission. This source appears unresolved at 8.8 μm, implying a small circumstellar structure.

4. VLBA observations failed to detect continuum emission at 6 cm. The lack of “peristellar” emission is likely due to a high optical depth of the free-free emission, which arises at larger scales. Shorter wavelengths should be used to detect the expected centimeter emission associated with the X-ray emission.

5. The near to mid-IR properties of YLW 15 show that VLA 1 is less luminous than VLA 2 in this wavelength range. This could be due to a lower bolometric luminosity of VLA 1 compared with VLA 2 or alternatively indicate that VLA 1 is a more embedded YSO, and thus, younger or less evolved, than VLA 2. VLA 2 has the SED properties of a typical Class I YSO. Therefore, VLA 1 could be either in the same evolutionary state than VLA 2 or either in the Class 0 to Class I transition.

6. VLA 1 appears to be more massive but more embedded or, alternatively, less luminous than VLA 2. This result is apparently against the expected evolutionary scenario, where one expects that the more massive YSO in a binary system is also the more evolved and luminous YSO.

7. YLW 16A is detected with the VLA. Its position coincides well with the near-IR and X-ray emission observed in the region.

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