HIGH-ANGULAR-RESOLUTION OBSERVATIONS AT 7 MM OF THE CORE OF THE QUADRUPOLAR HH 111/121 OUTFLOW

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ABSTRACT

We present sensitive, high-angular-resolution (0.05′′) Very Large Array continuum observations made at 7 mm of the core of the HH 111/121 quadrupolar outflow. We estimate that, at this wavelength, the continuum emission is dominated by dust, although a significant free–free contribution (∼30%) is still present. The observed structure is formed by two overlapping, elongated sources approximately perpendicular to each other as viewed from the Earth. We interpret this structure as either tracing two circumsolar disks that exist around each of the protostars of the close binary source at the core of this quadrupolar outflow, or a disk with a jet perpendicular to it. Both interpretations have advantages and disadvantages, and future high-angular-resolution spectroscopic millimeter observations are required to favor one of them in a more conclusive way.

Key words: binaries: general – ISM: individual (HH 111) – ISM: jets and outflows – radio continuum: ISM

1. INTRODUCTION

It is generally accepted that most stars form in binary or multiple systems (Lada & Lada 2003). Furthermore, in the case of low- and intermediate-mass stars, it is also known that the process occurs with the presence of an accretion disk and a collimated outflow. From these two facts, it follows that binary disk–jet systems should be common in regions of low-mass star formation. However, in practice these systems are hard to detect and identify and only a few have been studied in detail (e.g., Rodríguez et al. 1998; Anglada et al. 2004; Monin et al. 2007). Furthermore, it is still unclear if both of the members of a binary system will be able to maintain the disks and outflows that characterize the formation of single stars. For example, both of the binary stars that form L1551 IRS5 are believed to possess disks and jets (Rodríguez et al. 2003; Lim & Takakuwa 2006), while it is known that only one of the stars that forms the SVS 13 close binary system is associated with detectable circumstellar dust emission that is probably tracing a disk (Anglada et al. 2004).

One of the most interesting cases of a binary source that is known to exhibit independent outflows, which are most probably associated with each of the components of the binary, is HH 111 (Reipurth et al. 1999). Located in Orion at a distance of 414 pc (Dent et al. 2007), the optical HH 111 jet was discovered by Reipurth (1989). It is an extremely well-collimated jet, aligned approximately in the east–west direction (at a P.A. of ∼97°), whose knots move in the plane of the sky with velocities on the order of several hundred km s⁻¹ (Reipurth et al. 1992). Reipurth et al. (1997) found that this optical jet is part of a giant HH complex extending over 7.7 pc. This giant HH complex is very straight, suggesting great stability over the 10^4 years of its lifetime.

Near-infrared observations (Gredel & Reipurth 1993, 1994) revealed a second bipolar flow, named HH 121, that emerges from about the same position as the optical outflow and is aligned approximately in the north–south direction (at a P.A. of ∼35°). This result suggested the presence of a close binary source in this region. Both the optical and the infrared outflows are detected as bipolar molecular outflows (Cernicharo & Reipurth 1996; Nagar et al. 1997; Lefloch et al. 2007).

At the center of the quadrupolar outflow is the source IRAS 05491+0247 (VLA 1), a suspected class I binary with a total luminosity of about 25 L☉ (e.g., Stapelfeldt & Scoville 1993; Yang et al. 1997). To advance our understanding of this source, a high-angular-resolution image at millimeter wavelengths was needed to compare with the information available for the quadrupolar outflow.

2. OBSERVATIONS

The 7 mm continuum observations were made in the A configuration of the Very Large Array (VLA) of NRAO,5 during 2006 February 10 and 15. The central frequency observed was 43.34 GHz and we integrated on-source for a total of approximately 5 hr. The absolute amplitude calibrator was 1331+305 (with an adopted flux density of 1.46 Jy) and the phase calibrator was 0552+032 (with bootstrapped flux densities of 0.84 ± 0.01 Jy and 0.89 ± 0.04 Jy for the first and the second epochs, respectively). The phase noise rms values were about 20′′ and 30′′ for the first and the second epochs, respectively, indicating good weather conditions. The phase center of the observations was at α(2000) = 05h51m46.25s; δ(2000) = +02°48′29.6″.

The data were acquired and reduced using the recommended VLA procedures for high-frequency data, including the fast-switching mode with a cycle of 120 s. The effective bandwidth of the observations was 100 MHz.

3. ANALYSIS

3.1. 7 mm Data

In Figure 1 we show the 7 mm image of the core of the HH 111/121 quadrupolar outflow. An unusual structure is evident in the image. The structure can be described as two overlapping, elongated sources aligned in the plane of the sky.
and approximately perpendicular to each other. We have fitted the emission with two Gaussian ellipsoids using the task JMFIT of the AIPS package (see Table 1). The data image and the model image are shown in Figure 2. In what follows, we will interpret this 7 mm structure, as well as that seen at 3.6 cm, of the two nearly perpendicular structures observed at 7 mm are similar to those observed at 3.6 cm, at 7 mm are we seeing two jets, two disks, or a jet and a disk? To address these interpretations, we first discuss additional continuum observations of the region.

3.2. Flux Densities at Other Wavelengths

We searched in the literature and the VLA archives for additional data points of the continuum flux density of this source. In Table 2 we present a summary of the total flux densities obtained for the region. The observations are not taken simultaneously and, if time variations are present, this will lead to an erroneous determination of the spectral indices. We also note that the observations are taken at different angular resolutions and that this may affect the comparison. The VLA is sensitive only to emission in angular scales smaller than or comparable to ~25 times its angular resolution, while for the Owens Valley Radio Observatory (OVRO), the largest detectable angular scale is about 10 times the angular resolution. In particular, the 7 mm data were taken with the highest angular resolution (and thus the smallest detectable angular scale) and we may be underestimating the total flux density at this wavelength in comparison with the other observations, which are all taken at lower angular resolutions. Lower-angular-resolution VLA observations at 7 mm are needed to determine the complete flux density of HH 111.

The total continuum flux density at 7 mm is about 40\% larger than the addition of the individual flux densities given in Table 1. This difference results from the presence of faint, extended 7 mm emission that is not accounted for in the individual Gaussian fits. Analysis of the residual (with the Gaussian fits removed) image suggests that this faint emission seems to extend over a diameter of ~0\'.3, but its nature is unclear. As can be seen from Table 2 and in Figure 3, the flux density is relatively flat in the centimeter range and rises rapidly above ~30 GHz. We have fitted the data points with the sum of two power laws of the form

\[ S_v(\text{total}) = S_{8.4 \text{GHz}}(\text{free–free})(v/8.4 \text{GHz})^{0.3} + S_{43.3 \text{GHz}}(\text{dust})(v/43.3 \text{GHz})^{2.5}, \]

where the first term is intended to represent the contribution of free–free emission from the ionized outflow and the second term is intended to represent the contribution of dust emission from the disks. Since we have four parameters to fit and only five data points, this fit is only intended to show that the data can be reasonably fitted with the sum of two power laws. In Figure 3 we show the fit for \( S_{8.4 \text{GHz}}(\text{free–free}) = 0.93 \text{ mJy} \) and \( S_{43.3 \text{GHz}}(\text{dust}) = 3.6 \text{ mJy} \). Under this interpretation, the 8.44 GHz emission is clearly dominated by free–free, with only

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ime 2. Contour images of the 7 mm continuum emission (left) and of the model with two Gaussian ellipsoids. Contours are $-4, -3, 3, 4, 5, 6, 8, 10$, and $12$ times $56 \mu$Jy beam$^{-1}$, the rms noise of the image. The half-power contour of the synthesized beam ($0''.053 \times 0''.043$ with a P.A. of $-5^\circ$) is shown in the bottom left corner of the data image.

Table 1
Decomposition of the 7 mm Continuum Emission in Two Components

| Component     | $\alpha$(J2000)$^a$ | $\delta$(J2000)$^a$ | Total Flux Density (mJy) | Deconvolved Angular Size$^b$ |
|---------------|----------------------|----------------------|--------------------------|-----------------------------|
| North–South   | 05 51 46.2545        | 02 48 29.660         | $2.2 \pm 0.3$            | $0''.15 \pm 0''.02 \times 0''.05 \pm 0''.01$; $+23^\circ \pm 6^\circ$ |
| East–West     | 05 51 46.2521        | 02 48 29.659         | $1.4 \pm 0.3$            | $0''.20 \pm 0''.05 \times \leq 0''.04$; $+116^\circ \pm 7^\circ$ |

Notes.

$^a$ Units of right ascension are hours, minutes, and seconds and units of declination are degrees, arcminutes, and arcseconds. The absolute positional accuracy is estimated to be $0''.01$.

$^b$ Major axis $\times$ minor axis; position angle of major axis.

Table 2
Total Flux Densities for the Core of the HH 111/121 Quadrupolar Outflow

| Frequency (GHz) | Flux Density (mJy) | VLA Configuration | Angular Resolution ($''$) | VLA Project Code | Epoch of Observation | Reference                  |
|-----------------|---------------------|--------------------|---------------------------|------------------|----------------------|---------------------------|
| 4.86            | $0.83 \pm 0.09$     | CnB                | $\sim 4.0$                | AA 183           | 1994 Sep 21          | VLA archive$^a$           |
| 8.44            | $1.01 \pm 0.11$     | A                  | $\sim 0.25$               | AR 2778          | 1992 Nov 02 + 1994 Apr 30 | Reipurth et al. (1999)$^a$ |
| 14.94           | $1.94 \pm 0.40$     | D                  | $\sim 5.7$                | AR 241           | 1991 May 17          | Rodríguez & Reipurth (1994)$^a$ |
| 43.34           | $5.15 \pm 0.52$     | A                  | $\sim 0.05$               | AT 325           | 2006 Feb 10+15       | This paper                |
| 110.2           | $46.0 \pm 7.0$      | $\ldots^b$        | $\sim 7.0$                | $\ldots^b$      | 1989 Dec–1990 May    | Stapelfeldt & Scoville (1993) |

Notes.

$^a$ Flux densities from our analysis of the data.

$^b$ Data taken with the Owens Valley Radio Observatory Millimeter Interferometer.

$\sim 6\%$ of dust contribution. On the other hand, the 43.34 GHz emission is dominated by dust, with a $\sim 30\%$ contribution from free–free. Following Rodríguez et al. (2007) and Hunter et al. (2006), we estimate the total mass in the dust to be on the order of $0.1 M_\odot$. For this estimate, a dust temperature of $45$ K was used, following the assumptions of Stapelfeldt & Scoville (1993).

3.3. Two Jets?

The excess of 7 mm emission with respect to the value expected from the extrapolation of the centimeter measurements rules out the possibility that at 7 mm we are simply observing two jets, since we have estimated that a significant fraction ($\sim 70\%$) of the 7 mm emission is due to dust. However, we cannot fully rule out the possibility that we are seeing a core dominated by dust emission with the extended emission dominated by free–free emission.

3.4. Two Disks?

The two-disks interpretation is suggested by the fact that at 3.6 cm the structure with the larger flux density is the east–west one, while at 7 mm this is true for the north–south structure (see Figure 1 and Table 1). Rodríguez et al. (2008), from a comparison between the momentum rate in the molecular outflow and the radio continuum emission from the
It is difficult to explain the lifetime of $10^4$ years of the HH 111 jet and its remarkable stability over this period. On the other hand, it should be noted that Reipurth et al. (1992) have suggested that the separation of bright knots in the optical flow are consistent with a timescale of variation of the central source of 40 years.

These last two difficulties are mitigated if we consider that the real separation is much larger than the projected one. A physical separation of 105 AU would be consistent with the values of 35 AU for tidally truncated radii. The orbital period would now be about 800 years and the timescale for alignment $\sim 1.6 \times 10^4$ years, consistent with the lifetime of the system. However, if we define the physical separation as $r$, the probability of observing it at a projected separation of $r'$ or smaller is

$$P(\leq r') = 1 - [1 - (r'/r)^2]^{1/2},$$

which, for $r' = 15$ AU and $r = 105$ AU, gives $P(\leq r') \simeq 0.01$.

We conclude that either we are observing the binary at an unlikely orientation, that disks in binary systems are more stable and independent than previously thought, or that the interpretation is incorrect.

### 3.5. One Jet and One Disk?

This final interpretation implies that at 7 mm we are seeing a north–south structure dominated by dust emission that traces a disk and an east–west structure that could be related to the jet that powers the optical HH 111 outflow. A major advantage with this interpretation is that the structures have a relative angle of $93^\circ \pm 9^\circ$, very close to perpendicularity. The east–west structure has a flux density of $0.7 \pm 0.2$ mJy at 3.6 cm and of $1.4 \pm 0.3$ mJy at 7 mm. This results in a spectral index of $0.4 \pm 0.2$, which is consistent with the value expected for a thermal jet (e.g., Anglada 1996; Eisloffel et al. 2000).

However, this interpretation also presents some difficulties. The east–west structure at 3.6 cm has a position angle of $97^\circ \pm 1^\circ$, while the east–west structure at 7 mm has a position angle of $116^\circ \pm 7^\circ$. In other words, the two structures are not nearly parallel, as would be expected if the 3.6 cm emission were the larger-scale counterpart of the 7 mm jet emission. Under this interpretation, all the 7 mm emission is related to the HH 111 disk–outflow system and there is no evidence at this wavelength of the HH 121 system. Of course, it should be pointed out that the dust and free–free emission from the HH 121 system are probably present in the image at a low level, but that we cannot disentangle their presence given the modest signal-to-noise ratio of the data.

### 4. CONCLUSIONS

Our main conclusions follow.

1. Our high-angular-resolution ($0''05$) VLA continuum 7 mm observations of the core of the HH 111/121 quadrupolar outflow reveal a structure that can be described as two overlapping, elongated sources that appear approximately perpendicular to each other in the plane of the sky.

2. We discuss possible interpretations for this structure and conclude that the most viable ones are that we are observing either two orthogonal disks around separate protostars or a disk with a perpendicular jet. Both interpretations have advantages and disadvantages, and high-angular-resolution spectroscopic millimeter observations (possible only in the future with the Atacama Large Millimeter Array) are required to disentangle what is occurring at the core of this quadrupolar outflow.
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