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THE MULTIPLE PROTOSTELLAR SYSTEM L1551 IRS5 AT 5 AU RESOLUTION

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ABSTRACT

We present images of L1551 IRS5 at angular resolutions as high as ~30 mas, corresponding to a spatial resolution of ~5 AU, made at 7 mm with the VLA. Previously known to be a binary protostellar system, we show that L1551 IRS5 is likely a triple protostellar system. The primary and secondary components have a projected separation of ~46 AU, whereas the tertiary component has a projected separation of ~11 AU from the primary component. The circumstellar dust disks of the primary and secondary components have dimensions of ~15 AU, whereas that of the tertiary component has a dimension of ~10 AU. Their major axes are closely, but not perfectly, aligned with each other, as well as the major axis of the surrounding flattened, rotating, and contracting molecular condensation (pseudodisk). Furthermore, the orbital motion of the primary and secondary components is in the same direction as the rotational motion of this pseudodisk. We suggest that all three protostellar components formed as a result of the fragmentation of the central region of the molecular pseudodisk. The primary and secondary components, but apparently not the tertiary component, each exhibits a bipolar ionized jet that is centered on and which emergers perpendicular to its associated dust disk. Neither jets are resolved along their base, implying that they are driven within a radial distance of ~2.5 AU from their central protostars. Finally, we show evidence for what may be dusty matter streams feeding the two main protostellar components.

Key words : stars: formation — stars: multiple — stars: outflows — stars: individual (L1551 IRS5)

I. INTRODUCTION

The majority of stars, both on the pre-main-sequence and main-sequence, are members of binary or multiple systems. The formation of binary/multiple stars is therefore believed to be the primary branch of star formation. Yet, much of our understanding of star formation is based largely on theoretical models and observations of what are apparently single nascent stars.

Both theoretical simulations and observational studies of binary/multiple stars in formation face difficult challenges. The average orbital separation of low-mass stars in binary or multiple systems on the pre-main-sequence and main-sequence is ~50 AU, which corresponds to an angular separation of just ~0.″4 even at the distance of the nearest star-forming regions at ~140 pc. By comparison, the present generation of millimeter/sub-millimeter interferometers operating at wavelengths shorter than about 4 mm can only attain angular resolutions of at best ~0.″5. This makes it difficult if not impossible to study the individual protostellar components of many binary/multiple systems, as is necessary to properly test theoretical models of binary/multiple star formation. The currently favoured models invoke fragmentation of a dense molecular core into two or more star-forming condensations, which may suffer orbital decay through dynamical interactions to form an even more closely-separated binary or multiple system (e.g., review by Bodenheimer et al. 2000). Gravitational capture from close passages of neighbouring protostars may also form closely-separated binary systems, and may be necessary to form those systems with orbital separations $\lesssim$ 10 AU (Bate et al. 2002).

At cm wavelengths, the Very Large Array (VLA) has played a pivotal role in studies of bipolar ionized jets from protostars. With its ability to attain angular resolutions as high as ~0.″1, the VLA brings us as close to the central driving engine of bipolar outflows as is currently possible on most protostars. With the installation of 7-mm receivers on the VLA, imaging of dust emission from protostars at high angular resolutions also has become feasible. Here, we present observations of the multiple protostellar system L1551 IRS5 at 7 mm with the VLA. L1551 IRS5 resides in the Tauris molecular cloud complex at a distance of ~140 pc. The images presented here are the highest angular and

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spatial resolution images of protostellar dust disks and bipolar ionized jets ever made, and provide an important test of models for the formation of multiple stars and their bipolar ionized jets.

II. OBSERVATIONS AND RESULTS

We observed L1551 IRS5 with the VLA in A configuration, together with the Pie Town (PT) antenna, at 7 mm on 1 February 2002. The Pie Town antenna belongs to the Very Long Baseline Array (VLBA), but when required can be linked with the VLA to improve the angular resolution of this array by a factor of nearly two.

In Figure 1, we show our image of L1551 IRS5 made with the VLA only, convolved to an angular resolution of 62 × 47 mas (8.7 × 6.6 AU). This image has nearly identical angular resolution with but higher sensitivity than that made about 5 years earlier by Rodríguez et al. (1998), when only about half of the VLA antennas were equipped at 7 mm. Two sources aligned north-south and separated by 328 mas (46 AU) can be seen, which in the study of Rodríguez et al. (1998) were interpreted as binary circumstellar dust disks. These components are hereafter referred to as the northern and southern components respectively.

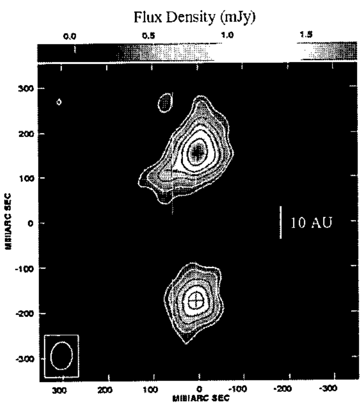

Fig. 1.— Our VLA A-array image of L1551 IRS5 at 7 mm, observed on 1 February 2002. The synthesized beam, shown at the lower left corner, has a size of 62 × 47 mas (8.7 × 6.6 AU). The three crosses mark the location of the individual protostellar components inferred from Figure 2. At this angular resolution, the bipolar ionized jets cannot be separated from their associated dust disks.

A comparison of the relative orientations of the northern and southern components with the earlier image of Rodríguez et al. (1998) reveals that the southern component is moving eastwards with respect to the northern component. This relative motion is the same as that measured by Rodríguez et al. (2003a) for the centers of their respective bipolar ionized jets at 3.5 cm with the VLA. This motion presumably reflects the orbital motion of the two protostellar components, and is in the same direction as the rotational motion of a much larger flattened and contracting molecular condensation enveloping the entire system (Momose et al. 1998; Takakuwa at al. 2004).

Our map of Figure 1 shows a prominent extension to the southeast of the northern component. This extension cannot be seen in the image of Rodríguez et al. (1998), which on the other hand shows a relatively weak extension to the northwest. We have reanalyzed their data, and believe that this northwestern extension is an artifact due to the limited dynamic range of their map.

In Figure 2, we show our images of L1551 IRS5 made with the VLA and PT-antenna combined. The image in the upper panel was made with robust weighting to obtain an angular resolution of 45 × 37 mas (6.3 × 5.2 AU). The prominent extension to the southeast of the northern component in Figure 1 now appears as a separate component at an angular distance of 79 mas (11 AU) from the northern component. We hereafter refer to this component as the tertiary component. Both the northern and southern components can now be seen to each have a cross-like structure; i.e., they are both extended in the northwest-southeast and northeast-southwest directions. The tertiary component, however, is extended only along the northwest-southeast direction.

The image in the lower panel of Figure 2 was made with a slightly stiffer robust weighting to obtain a slightly higher angular resolution of 43 × 32 mas (6.0 × 4.5 AU). L1551 IRS5 is known to exhibit twin bipolar ionized jets, seen at both optical and cm wavelengths, that are closely but not perfectly aligned with each other. The orientation of these jets as inferred by Rodríguez et al. (2003b) from images at 3.5 cm, which trace the jets on larger spatial scales than at 7 mm, are indicated in the figure; this also is the approximate orientation of a very large-scale bipolar molecular outflow. The northern jet is perfectly aligned with the northwest-southeast extension of the northern component, and the southern jet with the northwest-southeast extension of the southern component. We interpret the extensions orthogonal to these jets as inclined circumstellar dust disks. The tertiary component is quite closely aligned with the circumstellar dust disks of both the northern and southern components, and we interpret this component also as a inclined circumstellar dust disk. If correct, this makes L1551 IRS5 a triple protostellar system.

On 2003 October 27 and November 6 we observed L1551 IRS5 at 7 mm with the VLA in B-array, which is more sensitive to extended structures. In Figure 3, we show the resulting images convolved to an angular resolution of 0.″22 (30 AU) and 0.″12 (17 AU) respectively. A weak extension can be seen in the upper panel of Figure 3 to the northwest of the northern component; similarly, a weak extension can be seen in the lower panel of Figure 3 to the southeast of the southern component. These extensions may trace matter streams from

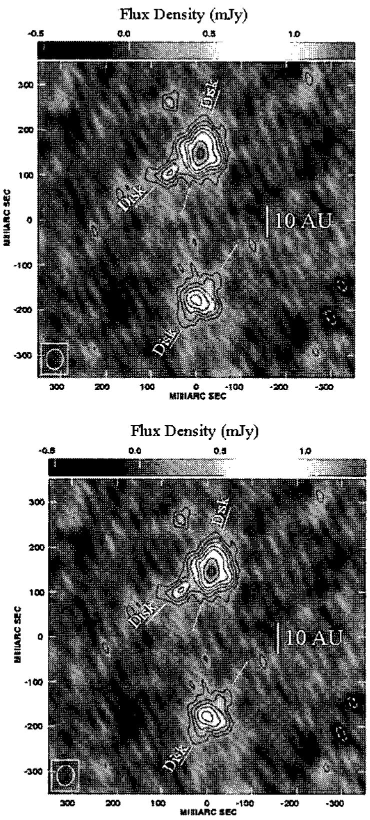

Fig. 2.— Our VLA A+PT-array image of L1551 IRS5 at 7 mm, observed on 1 February 2002. The synthesized beam is shown at the lower left corner of each panel. Upper panel: Robust=0.5 weighting to give an angular resolution of 45 × 37 mas (6.3 × 5.2 AU). The three identified circumstellar dust disks are indicated. The tertiary disk was not previously detected in observations at a factor of two lower sensitivity and angular resolution by Rodríguez et al. (1998). Lower panel: Robust=0 weighting to give a slightly higher angular resolution of 43 × 32 mas (6.0 × 4.5 AU). The orientations of two bipolar ionized jets as seen at much larger spatial scales by Rodríguez et al. (2003b) are indicated by arrows.

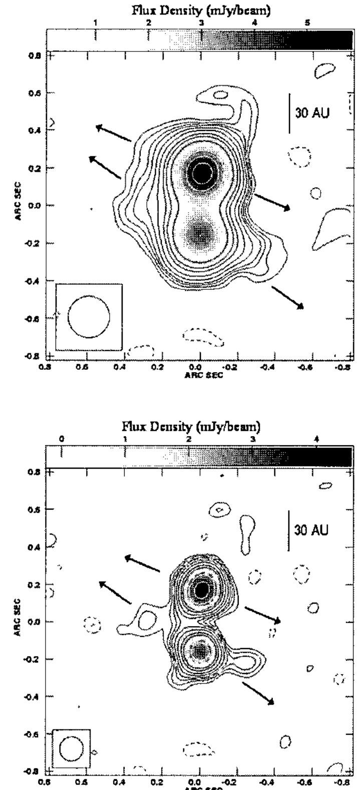

Fig. 3.— Our VLA B-array image of L1551 IRS5 at 7 mm, observed on 2003 October 27 and November 6. The synthesized beam is shown at the lower left corner of each panel. Upper panel: Image convolved to an angular resolution of 0.″22 (30 AU). Lower panel: Image convolved to an angular resolution of 0.″12 (17 AU). The orientations of two bipolar ionized jets as seen at much larger spatial scales by Rodríguez et al. (2003b) are indicated by arrows. The weak extensions to the northwest of the northern component (upper panel) and southeast of the southern component (lower panel) may trace matter streams.

the surrounding envelope (or circumtriple disk) feeding the circumstellar disks of the northern and southern protostellar components.

III. DISCUSSION

Our 7-mm image of L1551 IRS5 traces both dust and ionized gas, each of which contributes roughly comparably to the total emission observed. At the brightness temperature sensitivity of Figure 1, the circumstellar dust disks of the northern and southern components have dimensions of ∼15 AU, and the circumstellar dust disk of the tertiary component a dimension of ∼10 AU. This is about an order of magnitude smaller than the size of circumstellar dust disks inferred around single protostars and pre-main-sequence stars. Such small circumstellar disks, however, are expected from theoretical simulations of closely-separated binary systems. In these simulations, gravitational tidal forces quickly truncate the circumstellar disks of the individual protostellar components to a small fraction of their orbital separation (Artymowicz & Lubow 1994).

The major axes of the three circumstellar disks are aligned to within an angle of ∼26°. This close alignment, if not a coincidence, indicates that all three circumstellar dust disks may have formed from a common structure. As mentioned earlier, these protostellar components are surrounded by a large and massive, flattened and rotating, contracting molecular condensation, perhaps a pseudodisk as is predicted by theoretical models of ambipolar diffusion (Galli & Shu 1993a,b). The major axes of the three dust disks are closely aligned with the major axis of this molecular condensation. Furthermore, the orbital motion of the northern and southern components are in the same direction as the rotational motion of this condensation. We therefore suggest that the three protostellar components formed as a result of the fragmentation of the cental region (core) of this molecular pseudodisk. Theoretical simulations demonstrate that, under appropriate physical conditions, the core of such large and massive disks can be rotationally unstable and fragment (Bonnell 1994, and references therein).

The bipolar ionized jets associated with the northern and southern components are each centered on and emerge perpendicular to their associated dust disks. Neither jets are spatially resolved at their base even at a resolution of 5 AU, implying that they originate within a radial distance of 2.5 AU from the central protostar. This places very stringent constraints on theoretical models for driving bipolar outflows from protostars. Shang et al. (2004) recently compared the structure of the bipolar ionized jets from L1551 IRS5 imaged at $\sim 0''.1$ angular resolution by Rodríguez et al. (2003b) with the X-wind model of Shu et al. (1994). It will be interesting to see whether the structure of these jets continue to compare favourably with the X-wind model, or other models, at the higher angular resolutions of our observations. The non-detection of a bipolar ionized jet from the tertiary component implies that any such jet from this component must have a mass-loss rate of $\lesssim 5$ times lower than those of the northern and southern components (assuming that all have otherwise similar parameters).

The brightness temperature of the northern circumstellar disk is $\sim$300 K, and that of the southern and tertiary disks are $\sim$200 K. The measured brightness temperatures place a lower limit on the (average) temperature of the dust emission. The relatively high dust temperatures suggest that the disks are vigorously accreting material from their surroundings (c.f., Rodríguez et al. 1998). Simulations of close binary protostellar systems suggest that, within just a few binary orbits, the system clears a circumbinary gap of size a few times the binary separation (Artymowicz & Lubow 1994). Instead of accreting directly onto the circumstellar disks, infalling matter piles up onto a circumbinary disk. Nevertheless, transient matter streams can penetrate this gap and feed the circumstellar disks, at a time-averaged accretion rate similar to that of just a single central protostar (Artymowicz & Lubow 1994).

Our images do not show a circumtriple disk, but we may not have the brightness sensitivity to detect any such spatially-extended disk. On the other hand, our images show opposing extensions from the northern and southern component that may trace matter streams. Simulation show that such streams should impact the circumstellar disks at or near the observed locations (e.g., Artymowicz & Lubow 1994).

IV. CONCLUSIONS

Our high-resolution images of L1551 IRS5 properly resolve the circumstellar dust disks in this system for the first time. L1551 IRS5, previously thought to be a binary protostellar system, is likely a triple protostellar system. The small sizes of the three circumstellar dust disks are consistent with predictions of tidal truncation. Their orientations and orbital motion suggest that they formed from a common structure, which we suggest to be the fragmentation of the central region (core) of the surrounding molecular pseudodisk. We also detected what may be matter streams feeding the two main protostellar components.

The bipolar ionized jets of the two main protostellar components are centered on and emerge perpendicular to their respective dust disks. They are not resolved in width at their base, implying that they are driven within $\sim$2.5 AU of their respective protostars. No ionized jet was detected from the tertiary component, implying that (for otherwise the same parameters) any such jet has a mass-loss rate at least a factor of $\sim$5 lower.

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