Formation of Binary and Multiple Protostellar Systems

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Abstract

Most stars are born in systems comprising two or more stars. The creation of such multiple systems is one of the outstanding contemporary problems in star formation. We show that the two main components of the protostellar system L1551 IRS5 have circumstellar disks that are accurately aligned with each other, as well as the disk plane of their surrounding molecular condensation. These two components are probably in near circular orbital motion, with a clockwise orbital motion that matches the clockwise rotational motion of their surrounding condensation. These attributes provide a smoking gun for the formation of the two main components of L1551 IRS5 as a result of fragmentation in the central region of their parent molecular condensation.

It is often said that our Sun is an ordinary star. But the Sun is somewhat unusual in at least one aspect — it is a single star. By comparison, about two-thirds of Sun-like stars are members of binary or multiple systems. How and why nature preferentially creates such systems is one of the contemporary outstanding problems in star formation.

We now have a relatively good understanding for the formation of single stars like the Sun. Stars are born in clouds of dense molecular hydrogen gas, which themselves are formed when a passing spiral arm sweeps up the tenuous gas between stars. In such a molecular cloud, individual overdense regions called condensations contract due to gravity to give rise to a protostar. The inner regions of such condensations sometimes resemble rotating pancake structures (called pseudodisks), at the center of which lies the protostar surrounded by a circumstellar disk. Not all the material that passes through the circumstellar disk accretes onto the protostar; instead, a portion of this material is ejected in the form of a bipolar outflow. Over time the condensation either becomes depleted and/or is dispersed by the bipolar outflow (or both), leaving a newborn star surrounded by a now tenuous circumstellar disk.

How do binary or multiple star systems form? Today, there are two dominant schools of thought for the formation of binary and multiple systems. The first postulates that stars are created as individuals in the manner described above, and then subsequently captured by other stars (or star systems) to form binary (or multiple) systems. The other postulates that individual condensations break up in a process called fragmentation to produce multiple protostars.

Formation by capture forms systems with randomly aligned circumstellar disks and orbits. On the other hand, formation by fragmentation forms systems where the orbital motion of the protostars naturally follow the spin of their parent condensation. These predictions can be directly tested through observations of binary or multiple protostellar systems. As explained below, however, such observations are a challenge to make with the present generation of telescopes.

The separation between components of a typical binary system (or a hierarchical multiple system) is ~40 AU, the average separation between Pluto and the Sun. If located in the nearest star-forming region at a distance of ~140 pc (~456 light-years), just separating the individual protostellar components would require angular resolutions better than 0.″3, and imaging of their circumstellar disks higher angular resolution still. Furthermore, optical telescopes are not able to see into the gas and dust condensations that surround protostars. Only telescopes that operate at infrared or radio wavelengths can penetrate the condensation to study the embedded protostars. Of the telescopes that operate at such wavelengths, the only telescope with both the required sensitivity and angular resolution is the Very Large Array (VLA).

LDN 1551 IRS5 is an optically-invisible object located in a network of molecular clouds at a distance of ~456 light-years in the constellation Taurus. In early 2002, we used the full complement of the VLA at 7 mm to observed LDN 1551 IRS5. In addition, we used the Pie Town (PT) antenna of the Very Long Baseline Array (VLBA), linked in real time with the VLA, to approximately double the angular resolution.

The image of LDN 1551 IRS5 made from our observation is shown in Figure 1. As can be seen from the image, we detect the two known components oriented north-south separated by 46.3 ± 0.5 AU. These components are labelled and referred to hereafter as the northern, N, and southern, S, components. In addition, we discover for the first time a previously unknown third (3rd) component to the south-east of the N component separated by just 11.4 ± 1.2 AU. This triple protostellar system would therefore easily fit inside our own Solar System!

As can be seen in Figure 1, the major axes of both the N and S circumstellar disks are closely parallel with each other. Because these disks are resolved along their minor axes, we can also infer their inclination to the plane of the sky and find for both an inclination of ~60˚. Thus, the circumstellar disks of the N and S components are accurately aligned with each other. To study the orbital motion of these components, we have collected all available images of LDN 1551 IRS5 where the N and S components are spatially separated. These images reveal that the S component is moving to the south-east with respect to the N component. We find that the direction of motion is consistent with the S component describing a circular coplanar orbit about the northern component (i.e., with orbital plane parallel to the plane of the circumstellar disks).

LDN 1551 IRS5 is known to be surrounded by a molecular pseudodisk, which also is shown in

Figure 1. This pseudodisk exhibits clockwise rotation, has its major axis along the NNW to SSE direction, and is inclined by $\sim 64^{\circ}$ to the plane of the sky. Thus, the circumstellar disks of the N and S components are accurately aligned with the plane of this pseudodisk. Furthermore, the orbital motion of the N and S components is in the same direction as the rotational motion of their surrounding pseudodisk. These attributes constitute a smoking gun for the formation of the N and S protostars as a consequence of fragmentation in the inner region of their parent pseudodisk. This is the first time that such observational evidence in favour of the fragmentation model for binary star formation is available for any protostellar system.

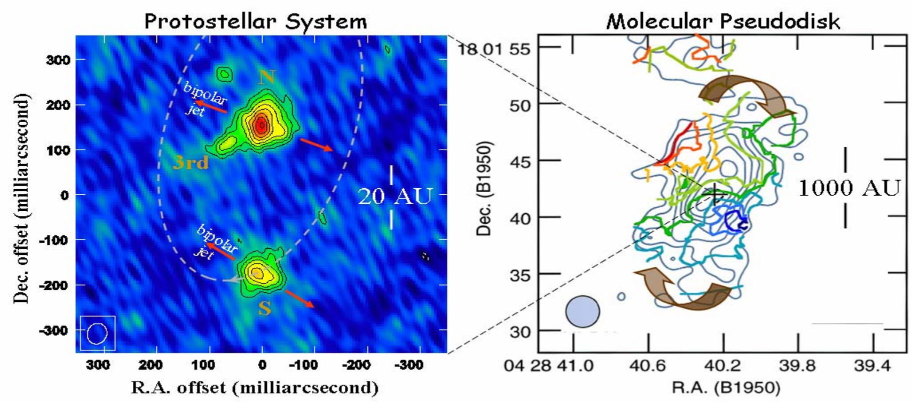

Figure1: Left panel: Our image of the protostellar system L1551 IRS5 made with the VLA. The two cross-like features (northern and southern components) correspond to circumstellar dust disks along one arm and bipolar jets (indicated by oppposing red arrows) along the other arm. The third feature to the lower left of the northern component is another circumstellar dust disk. The dashed partial ellipse indicates the clockwise orbital motion of the southern component with respect to the northern component. Right panel: An image of the molecular pseudodisk surrounding L1551 IRS5 (from Momose & Ohashi et al. 1998,. ApJ, 504, 314), whose position is indicated by a cross. The pseudodisk is rotating in the clockwise direction as indicated by the arrows. Notice that the circumstellar disks of the northern and southern components are aligned with the pseudodisk, and that the orbital motion of these components is in the same direction as the rotational motion of the pseudodisk. These attributes constitute a smoking gun for the formation of these two protostellar components as a result of fragmentation in the central region of the surrounding pseudodisk.

The way in which the 3rd component formed is less clear. Its circumstellar disk is not aligned with the N and S circumstellar disks, nor the surrounding pseudodisk. Theoretical studies show that gravitational forces can tilt the circumstellar disk of a protostar in the presence of more massive protostellar companions with larger disks. On the other hand, the 3rd component may have been captured. Future measurements of its orbital motion are required to distinguish between these two possibilites.

The work described here was published in the 10 December 2006 issue of the Astrophysical Journal (Lim & Takakuwa 2006, ApJ, 653, 425). This research was supported by a grant from the National

Science Council of Taiwan to Jeremy Lim at the ASIAA.

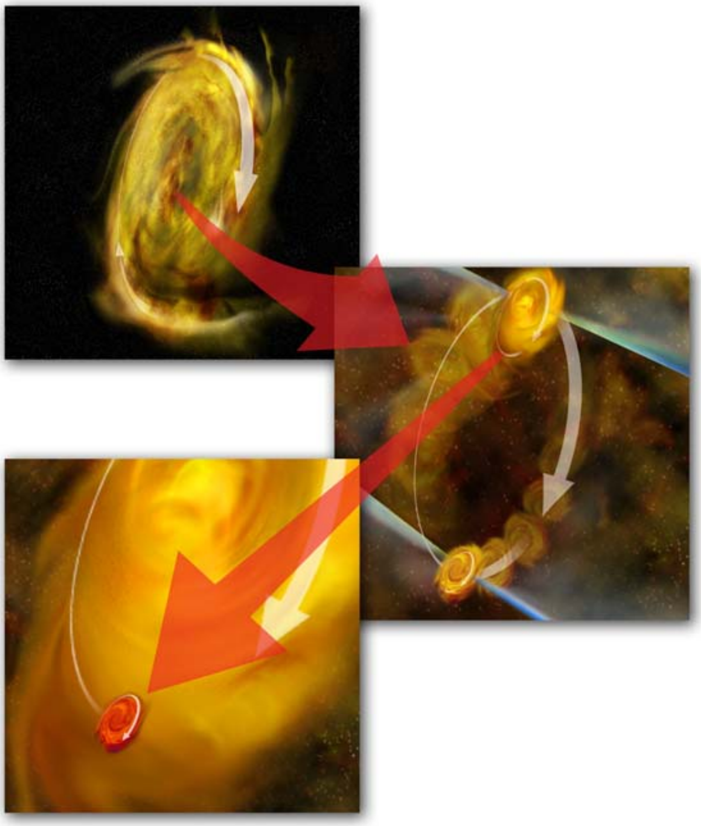

Figure 2: Artist's conception of proposed formation process for the multiple-star system L1551 IRS5, as revealed by observations with the Very Large Array (VLA) radio telescope. Top panel: large disk-like cloud of gas and dust rotates. Middle panel: two smaller disks of gas and dust fragment from the large disk and begin to condense into protostars, each having its own surrounding disk and shooting "jets" of material outward from the poles of its disk. Bottom panel: A third, smaller disk and protostar joins the system, either through the same fragmentation process or by being captured gravitationally by the larger protostars. Credit: Bill Saxton, NRAO/AUI/NSF