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MASSIVE STAR FORMATION

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RESUMEN

Durante las últimas décadas nuestro conocimiento sobre la formación de estrellas de tipo solar ha aumentado significativamente. Entre las siguientes fronteras en el campo tenemos al entendimiento de la formación estelar en los extremos, esto es, sobre como los objetos mucho más masivos (las estrellas OB) y mucho menos masivos (las enanas marrón) que el Sol se forman. Me concentraré en la formación de las estrellas masivas, discutiendo si el proceso se puede entender como una versión escalada de la formación de las estrellas de tipo solar, o si hay involucrados fenómenos de naturaleza distinta.

ABSTRACT

Over the last decades our knowledge on the formation of solar-type stars has increased significantly. Among the next frontiers in the field we have the understanding of stellar formation at the extremes, that is, how are objects much more massive (OB stars) and much less massive (brown dwarfs) than the Sun formed. I will focus on the formation of massive stars, discussing if it can be understood simply as a scaled-up version of the formation of solar type stars, or if phenomena of different nature are involved.

Key Words: **H II REGIONS — ISM: JETS AND OUTFLOWS — STARS: MASS LOSS — STARS: PRE-MAIN SEQUENCE**

1. INTRODUCTION

Our present understanding of star formation is primarily based on the observations of low-mass stars. In the current paradigm of the formation of low-mass stars (Shu, Adams, & Lizano 1987; Shu et al. 1993) the simultaneous presence of an accreting disk and of outflowing jets explains the major characteristics of the phenomenon. Although this accretion paradigm has been very successful in explaining what is observationally known about the formation of low-mass stars (e.g, Lada 1991), its applicability to the formation of massive stars remains under discussion. In particular, alternative mechanisms such as the merging of lower mass protostars to form a massive protostar have received serious consideration lately (e. g. Bonnell, Bate, & Zinnecker 1998).

Whether the massive protostars are formed by accretion or merging remains controversial. If massive O stars are formed by accretion we expect that disks and jets will be present in their earliest stages of evolution. On the other hand, if formed by coalescence of lower-mass stars neither well-collimated jets nor well-defined disks are expected. Thus, the search for jets and disks toward massive YSOs is crucial to understand their formation process.

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2. JETS ASSOCIATED WITH MASSIVE PROTOSTARS

The evidence for jets and/or disks toward massive YSOs is rather scarce. Collimated outflows have been found in only a handful of B-type protostars: IRAS 18162-2048 ($\mathcal{L} \sim 1.7 \times 10^4$ $L_\odot$; Martí, Rodríguez, & Reipurth 1993); Cepheus A HW2 ($\mathcal{L} \sim 1 \times 10^4$ $L_\odot$; Rodríguez et al. 1994); IRAS 20126+4104 ($\mathcal{L} \sim 1.3 \times 10^4$ $L_\odot$; Cesaroni et al. 1997); and G192.16-3.82 ($\mathcal{L} \sim 3 \times 10^3$; Shepherd et al. 1998; Devine et al. 1999; Shepherd, Claussen, & Kurtz 2001); AFGL 5142 ($\mathcal{L} \sim 3.0 \times 10^3$ $L_\odot$; Zhang et al. 2002); IRAS 18089-1732 ($\mathcal{L} \sim 3 \times 10^4$; Beuther et al. 2005). None of these objects exceeds a bolometric luminosity of 3×10^4 $L_\odot$ and are thus B0 ZAMS or later objects.

Until recently, there were no good cases of a collimated outflow from a young, luminous O-type protostar. The first reported candidate is IRAS 16547−4247, a luminous infrared source located at a distance of 2.9 kpc and with a bolometric luminosity of 6.2×10^4 $L_\odot$. Using ATCA and the VLA, Garay et al. (2003) and Rodríguez et al. (2005a) report the discovery and study of a triple radio source toward this region (see Fig. 1). The triple radio source shows a nearly linear structure, consisting of a compact central object and two outer lobes, separated by about 20″, symmetrically located from the central source. The positive spectral index of the central source is consistent with that expected for a radio thermal (free-free) jet (e. g. Anglada 1996; Rodríguez 1997). The radio emission from the lobes has negative spectral indices, characteristic of non-thermal emission. Similar non-thermal lobes have been found in jet systems such as Serpens and Cep A HW2 and they can be explained in terms of fast shock waves moving through a magnetized medium, where a small fraction of the electrons is accelerated to relativistic velocities (Crusius-Wätzel 1990; Henriksen, Ptuskin, & Mirabel 1991). The emission from the central object has a spectral index of 0.3, consistent with free-free emission from a thermal jet. These observations suggest that the jets found in the formation of low-mass stars are also produced in high luminosity objects, with IRAS 16547−4247 being the most luminous YSO object presently known to be in this stage.

It is very important to measure the proper motions of the lobes N-1 and S-1, since the detection of large values will corroborate the interpretation of IRAS 16547-4247 as a massive protostar. Jets from massive protostars are characterized by larger velocities (500-1000 km s^{-1}; Martí et al. 1995) than jets from low-mass protostars (where velocities below 300 km s^{-1} are the rule; e.g., Reipurth et al. 2002, Bally et al. 2002). A project to undertake these measurements is in development.

3. DISKS ASSOCIATED WITH MASSIVE PROTOSTARS

If good cases of jets associated with young massive stars are difficult to find, the situation is much worse for disks. As a matter of fact, over the last few years there have been several reports of disks in association with young massive stars that have been later questioned by other groups.

Chini et al. (2004) reported at 2.2 μm the silhouette of a possible accretion disk in M17. The proposed disk has a diameter of 20,000 AU, much larger than disks around low mass stars, that have diameters of about 200 AU or less. The emission at the center of their image is taken to trace the central, massive star. The velocity gradient observed in ^{1}3CO is taken to imply a central mass of about 15 $M_\odot$, assuming Keplerian rotation. The gas reservoir of the circumstellar disk is estimated to contain al least 100 $M_\odot$ of additional gas, providing in principle sufficient fuel for substantial further growth of the forming star. However, Sato et al. (2005) questioned these claims, concluding that the protostar is of intermediate mass only (with a mass between 2.5 and 8 $M_\odot$) and that the surrounding circumstellar envelope contains only 0.09 $M_\odot$.

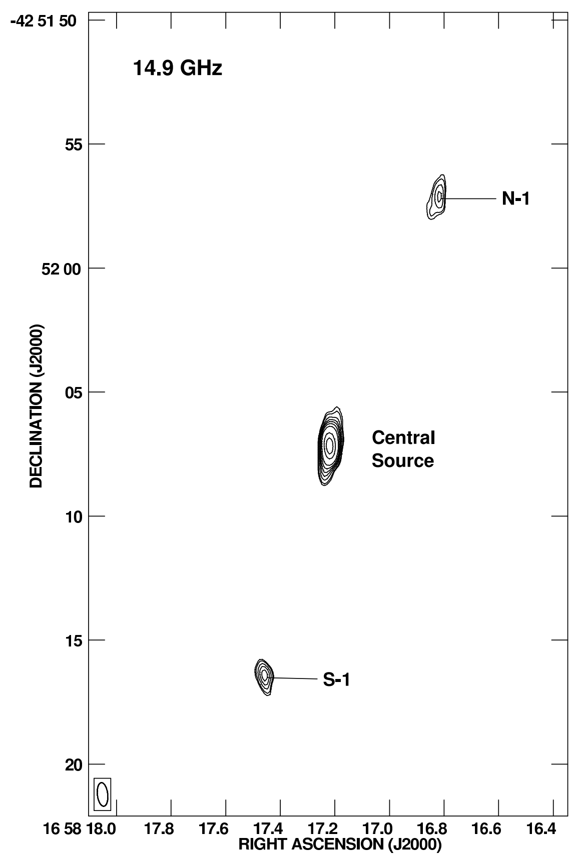

Fig. 1. VLA image at 14.9 GHz towards the young massive star IRAS 16547-4247. Contours are -5, 5, 6, 8, 10, 12, 15, 20, 40, 60, 80, 100, 140, and 180 times 87 μJy beam^{-1}, the rms of the image. The half power contour of the synthesized beam ($0.''95 \times 0.''42$; PA $= 6°$) is shown in the bottom left corner. This image was made with a ROBUST=5 weighting. Note the elongated central thermal jet and the two lobes N-1 and S-1.

Jiang et al. (2005) have argued that their near-infrared imaging polarimetry reveals an outflow/disk system around the Becklin-Neugebauer protostellar object in Orion, which is interpreted to have a mass of at least seven $M_\odot$. In their interpretation, the disk has a radius of 800 AU. However, Rodríguez et al. (2005b) and Gómez et al. (2005) have argued that the BN object had a close encounter, within a few AU, with another massive star only 500 years ago (see more discussion on this in the next section) and that it difficult to thing that such a large disk could have survived. Additional analysis of this source is required.

The best case up to now is that of the molecular disk around Cepheus A HW2. Studied with the SubMillimeter Array by Patel et al. (2005), they re-

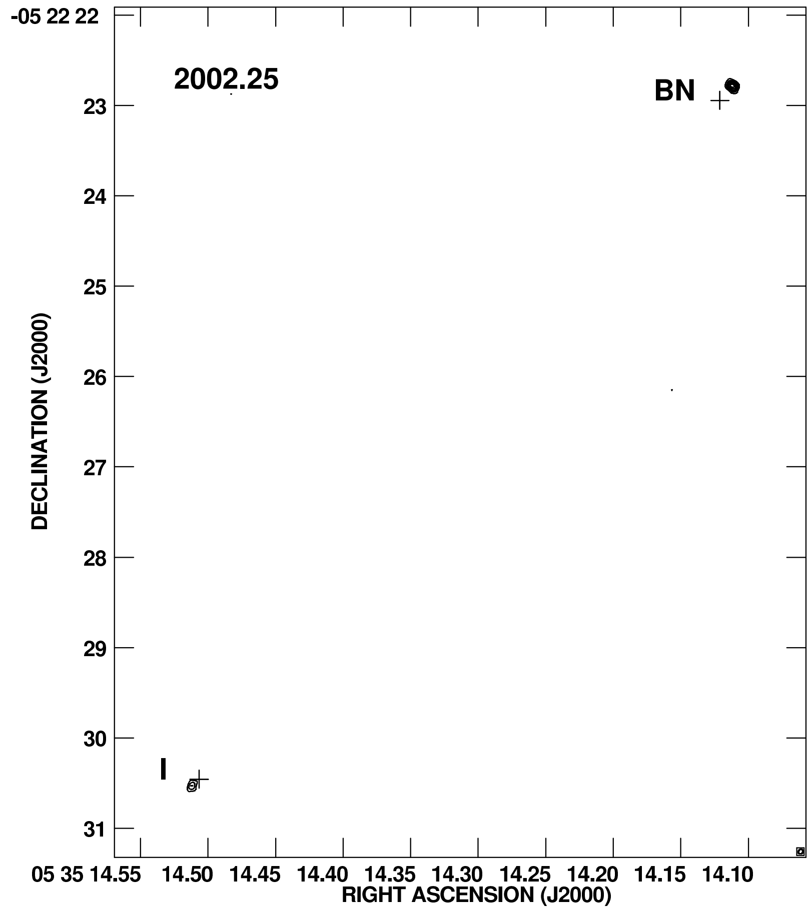

Fig. 2. VLA image at 7 mm for 2002.25 toward the BN object and the radio source I. The crosses mark the 1985.05 position of the sources. Contours are -4, 4, 8, 12, 16, 24, and 32 times 0.37 mJy beam^{-1}, the rms of the image. The half-power contour of the synthesized beam $0\rlap{.}''06 \times 0\rlap{.}''05; PA = -34^\circ$) is shown in the bottom right corner. Note the proper motion of both sources. Data from Rodríguez et al. (2005b).

port the presence of a flattened disk-like structure around this massive (15 $M_\odot$) protostar. They interpret the structure to trace a disk with a radius of about 330 AU and a mass of 1 to 8 $M_\odot$. Very recently, there have been reports of possible disks around IRAS 20126+4104 (Sridharan, Williams, & Fuller 2005) and AFGL 490 (Schreyer et al. 2006). In the case of IRAS 20126+4104 the disk is estimated to have dimensions of $\sim$1000 AU and a mass of $\sim$0.1 $M_\odot$. In the case of AFGL 490 the disk has a radius of $\sim$1500 AU and a mass of $\sim$1 $M_\odot$.

Finally, Franco-Hernández et al. (2006) have found evidence from dust and molecular SubMillimeter Array observations of a disk around the candidate O-type young star IRAS 16547-4247. This disk candidate has a radius of 1500 AU and a mass of a few solar masses, surrounding a star of about 40 $M_\odot$.

4. EVIDENCE FOR MERGERS?

With no clearcut case of a disk around a massive protostar, several authors have considered the possibility of merging to produce high mass stars. Most recently, Bally & Zinnecker (2005) have discussed this possibility. But, is there observational evidence for mergers? In fact, not much. One of the most tantalizing cases is that of the BN Object and the Radio Source I in Orion. The analysis by Rodríguez et al. (2005b) and Gómez et al. (2005) of Very Large Array archive data taken over the last two decades reveals that both the BN object and the radio source I have proper motions: the BN object has a proper motion of 12.6±0.6 mas yr^{-1} (corresponding to a velocity of 27±1 km s^{-1} at an adopted distance of 450 pc) to the northwest, while the radio source I has a proper motion of 5.6±0.7 mas yr^{-1} (corresponding to a velocity of 12±2 km s^{-1}) to the southeast. The motion of the two sources is nearly antiparallel, diverging from a point in between them, where they were located about 500 years ago (see Figure 2). These results suggest that the BN object and the radio source I were part of a multiple young stellar system that disintegrated in the recent past.

This result is related to the recent reanalysis by Bally & Zinnecker (2005) of the origin of the massive outflow originating near sources I and n (Allen & Burton 1993). This outflow is associated with gaseous fingers tracing strong bow shocks and has traditionally been interpreted as the result of a powerful explosion (e.g., Allen & Burton 1993; Schultz et al. 1999; Bally & Zinnecker 2005). The analysis of the proper motions of the fingers indicates that the explosion must have occurred less than a thousand years ago–a value of 1000 yr is obtained if the velocities have remained constant, but the actual time elapsed since the explosion may be somewhat less if there was significant deceleration. Bally & Zinnecker (2005) proposed that the explosion may have happened when source I (a 20 M$_\odot$ star) swallowed a relatively low-mass (1 M$_\odot$) object. Indeed, the total energy liberated by such a merger is about 3×10^{48} ergs, well in excess of the total energy carried by the outflow (4×10^{47} ergs; Kwan & Scoville 1976). Bally & Zinnecker (2005) also noted that the epoch of the explosion coincides roughly with the time when BN and I were very near to each other and argued that this was unlikely to be a coincidence. Consequently, they favored a scenario in which the BN object was ejected from I about 500 years ago, in the same dramatic merging event that produced the massive outflow.

REFERENCES

Allen, D. A., & Burton, M. G. 1993, Nature, 363, 54
Anglada, G. 1996, in ASP Conf. Ser. 93, Radio Emission from the Stars and the Sun, ed. A. R. Taylor & J. M. Paredes (San Francisco: ASP), 3
Bally, J., Heathcote, S., Reipurth, B., Morse, J., Hartigan, P., & Schwartz, R. 2002, AJ, 123, 2627
Bally, J. & Zinnecker, H. 2005, AJ, 129, 2281
Beuther, H., Zhang, Q., Sridharan, T. K., & Chen, Y. 2005, ApJ, 628, 800
Bonnell, I.A., Bate, M.R., & Zinnecker, H. 1998, MNRAS, 298, 93
Cesaroni, R., Felli, M., Testi, L., Walmsley, C.M., & Olmi, L. 1997, A&A, 325, 725
Chini, R., Hoffmeister, V., Kimeswenger, S., Nielbock, M., Nürnberger, D., Schmidtobreick, L., & Sterzik, M. 2004, Nature, 429, 155
Crusius-Wätzel, A.R. 1990, ApJ, 361, L49
Devine, D., Bally, J., Reipurth, B., Shepherd, D., & Watson, A. 1999, AJ, 117, 2919
Franco-Hernández, R. et al. 2006, in preparation
Garay, G., Brooks, K.J., Mardones, D., & Norris, R.P. 2003, ApJ, 587, 739
Gómez, L., Rodríguez, L. F., Loinard, L., Lizano, S., Poveda, A., & Allen, C. 2005, ApJ, 635, 1166
Henriksen, R.N., Ptuskin, V.S., & Mirabel, I.F. 1991, A&A, 248, 221
Jiang, Z., Tamura, M., Fukagawa, M., Hough, J., Lucas, P., Suto, H., Ishii, M., & Yang, J, 2005, Nature, 437, 112
Kwan, J., & Scoville, N. 1976, ApJ, 210, L39
Lada, C.J. 1991, in The Physics of Star Formation and Early Stellar Evolution, ed. C.J. Lada & N.D. Kylafis, (Dordrecht: Kluwer), 329
Martí, F., Rodríguez, L.F., & Reipurth, B. 1993, ApJ, 416, 208
Martí, F., Rodríguez, L.F., & Reipurth, B. 1995, ApJ, 449, 184
Patel, N. A. et al. 2005, Nature, 437, 109
Reipurth, B., Heathcote, S., Morse, J., Hartigan, P., & Bally, J. 2002, AJ, 123, 362
Rodríguez, L.F., Garay, G., Curiel, S., Ramírez, S., Torrelles, J.M., Gómez, Y., & Velázquez, A. 1994, ApJ, 430, L65
Rodríguez, L. F. 1997, in Herbig-Haro Flows and the Birth of Low Mass Stars, proceedings of IAU Symp. No. 182, eds. B. Reipurth & C. Bertout, p. 83 (Dordrecht: Kluwer)
Rodríguez, L.F., Garay, G., Brooks, K.J., & Mardones, D. 2005a, ApJ, 626, 953
Rodríguez, L. F., Poveda, A., Lizano, S., & Allen, C. 2005b, ApJ, 627, L65
Sato, S. et al. 2005, Nature, 434, 995
Schreyer, K., Semenov, D., Henning, Th., & Forbrich, J. 2006, ApJ, 637, L129
Schultz, A. S. B., Colgan, S. W. J., Erickson, E. F., Kaufman, M. J., Hollenbach, D. J., O'Dell, C. R., Young, E. T., & Chen, H. 1999, ApJ, 511, 282
Shepherd, D.S., Watson, A.M., Sargent, A.I., & Churchwell, E. 1998, ApJ, 507, 861
Shepherd, D.S., Claussen, M.J., & Kurtz, S.E. 2001, Science, 292, 1513
Shu, F.H., Adams, F.C., & Lizano, S. 1987, ARA&A, 25, 23
Shu, F.H, Najita, J., Galli, D., Ostriker, E., & Lizano, S. 1993, in Protostars and Planets III, eds. E.H. Levy & J.I. Lunine, 3
Sridharan, T. K., Williams, S. J., & Fuller, G. A. 2005, ApJ, 631, L73
Zhang , Q., Hunter, T.R., Sridharan, T.K., Ho, P.T.P. 2002, ApJ, 566, 982