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INTERFEROMETRIC MASER OBSERVATIONS FROM OUTFLOWS/DISKS IN STAR-FORMING REGIONS

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RESUMEN

Las observaciones interferométricas de la emisión maser de diversas moléculas (p.ej., H_2O, OH, CH_3OH) están constituyendo una herramienta muy eficaz para estudiar con gran resolución angular el gas molecular cercano a las protoestrellas. Gracias a ellas se ha observado que, en algunos casos, los máseres parecen trazar el disco que se forma alrededor del objeto estelar joven, mientras que en otros casos parecen trazar el propio flujo de material eyectado. En este artículo resumimos algunos de esos estudios observacionales, incluyendo los realizados muy recientemente mediante la poderosa técnica de interferometría de base muy larga (VLBI). Esas observaciones VLBI permiten estudiar los máseres con resolución angular de una pocas décimas de milisegundo de arco (equivalente a una resolución lineal de unas pocas décimas de unidad astronómica para objetos que se encuentran a una distancia de 500 pc), permitiendo con ello medir sus movimientos propios.

ABSTRACT

Interferometric maser observations of several molecular species (e.g., H_2O, OH, CH_3OH) provide a very powerful tool to study with high-angular resolution the molecular gas close to protostars. In this way, groups of maser spots have been found to be associated with radio-continuum jet sources in young stellar objects. In some cases, masers seem to be distributed in a band perpendicular to the central radio-continuum jet as might be expected for accretion disks. In other cases, the masers seem to be distributed along the jet source, consistent with being part of the outflow. Recently, a new way to study these star-forming regions through Very Long Baseline Interferometry (VLBI) measurements of the proper motions of the associated masers has emerged. These observations provide angular resolutions up to a few tenths of a milliarcsecond (a few tenths of an astronomical unit at a distance of 500 pc). Here we review some of these studies.

Key Words: **ISM: JETS AND OUTFLOWS — MASERS — STARS:FORMATION**

1. INTRODUCTION

Herbig-Haro (HH) objects, jets, molecular outflows, and masers are all signatures of the mass-ejection phase related with the first steps of evolution of young stellar objects (YSOs). According to theory, all these phenomena require the formation of a "disk-YSO-outflow" system and its subsequent interaction with the ambient medium to account for the observed properties (e.g., Shu, Adams, & Lizano 1987; Lizano & Torrelles 1995). However, the observational study of these systems has serious limitations. In fact, they are deeply embedded objects, often rendering them invisible at optical, and sometimes even at near-infrared wavelengths. Furthermore, the combination of faintness and small size scale of these systems ($\simeq$ 100 AU) requires observations with high sensitivity and high-angular resolution (better than $0\farcs1$ for objects at a typical distance of 500 pc, e.g., the Orion distance) in the wavelength range where the ambient medium is still transparent.

Interferometric maser observations at centimeter wavelengths provide a very powerful tool to study the gas very close to YSOs. In fact, maser emission of molecular species such as H_2O, OH, and CH_3OH trace high-density ($n(H_2) \simeq 10^7$–10^9 cm^{-3}) and warm ($T_K \simeq 100$ K) gas (e.g., Reid & Moran 1981; Forster & Caswell 1989; Elitzur 1992; Norris et al. 1998; van der Tak 2000). In addition, the ambient medium is transparent at these wavelengths, and the maser emission is strong (typical flux densities of several Jy) and can be studied with very high-angular resolution ($\simeq$ 0.4–100 mas; corresponding to 0.-2-40 AU at a distance of 500 pc) with powerful interferometers such as the Australia Telescope Compact Array (ATCA), Multi-Element Radio Linked Interferometer (MERLIN), Very Large Array (VLA), and

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Very Long Baseline Array (VLBA). In this paper we review some recent results obtained through interferometric measurements of masers, which are just starting to provide valuable information about the physical conditions and kinematics in both circumstellar disks and outflows.

2. MASERS TRACING DISKS/OUTFLOWS

The physical conditions of high-density ($\sim 10^7$–10^9 cm^{-3}) and temperature (a few 100 K) needed for maser excitation can be reached in both the inner parts of circumstellar disks around YSOs and in shocked gas within the associated winds. Therefore, a priori, masers in regions of star formation could trace both the circumstellar disks and the outflows. And in fact, this is what is observed. High-angular resolution observations of different species of masers at centimeter wavelengths have shown that in some cases masers seem to trace disks, but in other cases they seem to trace outflows. This "dichotomy" of masers either tracing disks or outflows is observed in both high- and low-mass YSOs. Some possible examples of masers tracing disks in star-forming region can be found in Orion K-L (Abraham & Vilas Boas 1994), IRAS 00338+6312 (Fiebig et al. 1996), Cepheus A HW2 (Torrelles et al. 1996), W75N VLA2 (Torrelles et al. 1997), NGC7538 (Minier, Booth, & Conway 1998), G309.92+048 (Norris et al. 1998), NGC2071 IRS3 (Torrelles et al. 1998a), AFGL 5142 (Hunter et al. 1999), and G192.16-3.82 (Shepherd & Kurtz 1999), while outflow examples can be found in W3(OH)-TW (Alcolea et al. 1992; Wilner, Reid, & Menten 1999), W49N (Gwinn 1994), L1448 C (Chernin 1995), W75N-VLA1 (Torrelles et al. 1997; Minier, Booth, & Conway 2000), NGC2071 IRS1 (Torrelles et al. 1998a), S106 FIR (Furuya et al. 1999, 2000), IRAS 20126+4104 (Moscadelli, Cesaroni, & Rioja 2000), and IRAS 21391+5802 (Patel et al. 2000).

The dichotomy of masers tracing disks/outflows has been suggested to be due to different stages of evolution of the YSOs, with masers in less evolved objects tracing bound motions and in more evolved ones tracing outflows (Torrelles et al. 1997, 1998a). However, this evolutionary sequence requires further testing, in particular because other effects such as the luminosity of the embedded sources, mechanical energy of the associated winds, and water abundance differences could play an important role. It is also interesting to note that this dichotomy is also observed in galaxies with water megamasers. In fact, while in NGC 4258 water masers trace a Keplerian disk around the nucleus of the galaxy (Miyoshi et al. 1995), in NGC 1052 the water masers are aligned along the axis of the radio jet emanating from the galactic core (Claussen et al. 1998).

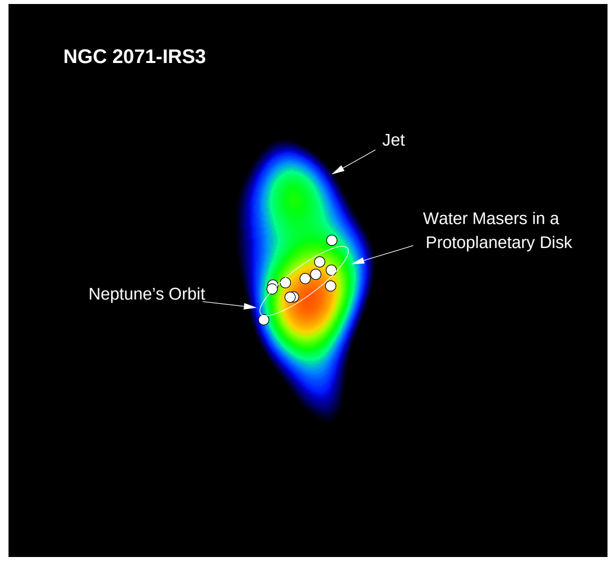

Fig. 1. VLA 1.3 cm continuum image of the radio jet NGC 2071 IRS 3. Dots indicate the position of the water masers. The ellipse shows the size of Neptune's orbit for comparison purposes. NOTE: THIS FIGURE IS AVAILABLE IN COLOR IN THE ELECTRONIC VERSION OF THIS ARTICLE, OBTAINABLE FROM `http://www.astroscu.unam.mx/~rmaa/`.

During the last few years a powerful cross-correlation technique using H_2O masers as the amplitude and phase reference has been applied successfully to *simultaneously* study with the VLA in its A configuration the 1.3 cm continuum and H_2O maser emission towards "disk-YSO-outflow" systems with $\sim 0\farcs08$ angular resolution (e.g., Torrelles et al. 1996, 1997, 1998a, 1998b). In the case of radio-continuum objects with strong H_2O masers associated to them, this technique can be applied to fully compensate the atmospheric "seeing" that affects observations at 1.3 cm, allowing the study of relatively weak continuum sources (a few mJy), as well as to obtain the relative position of the H_2O masers with respect to the radio-continuum source with an accuracy of a few milliarcseconds. With this powerful technique, first introduced by Reid & Menten (1990) to study evolved stars, it is possible to study maser structures with sizes of $\sim$ 25–100 AU (at distances of 500 pc) in YSOs. An example of results obtained with this cross-correlation technique is the low-mass star NGC 2071 IRS3 (Torrelles et al. 1998a). In Figure 1 we show for this YSO the spatial distribution of

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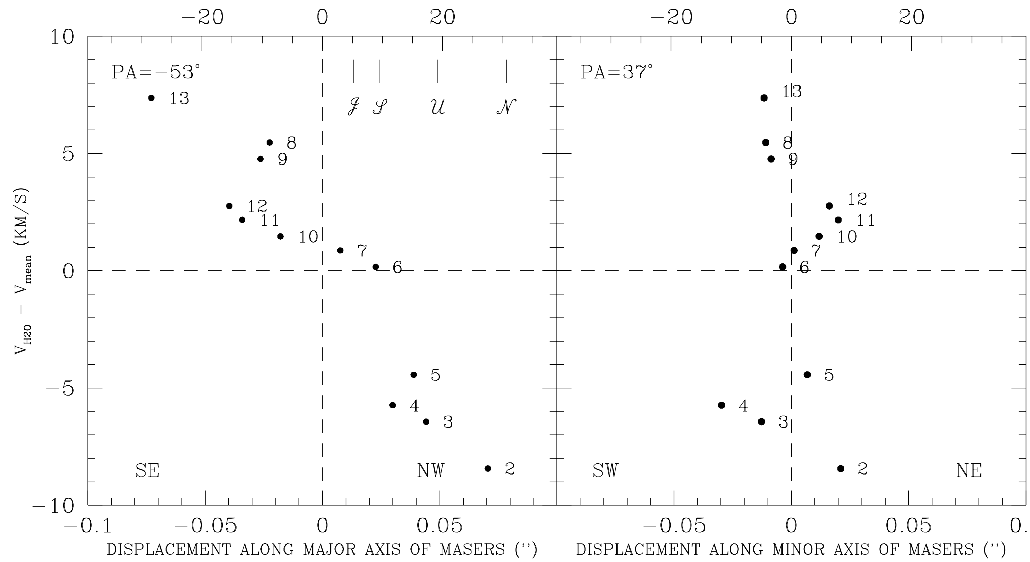

Fig. 2. Position-velocity distribution of the H_2O masers along the major (left panel) and minor (right panel) axes of the disk in NGC 2071 IRS 3. The spots are numbered according to their right ascension-declination position order. The orbital radius of Jupiter ($\mathcal{J}$), Saturn ($\mathcal{S}$), Uranus ($\mathcal{U}$), and Neptune ($\mathcal{N}$) are indicated in left panel for size comparison purposes with our planetary system (figure adapted from Torrelles et al. 1998a).

the water masers and the associated thermal radio-continuum jet, while in Figure 2 we show the velocity field of the masers. The spatio-kinematical distribution of the water masers in this source indicates that they are tracing a rotating protoplanetary disk of 20 AU radius around a protostar of 1 $M_\odot$ and oriented perpendicular to the associated radio jet. At the moment, this represents the smallest "disk-YSO-outflow" system ever detected with a direct measure of the velocity of rotation. Other sources where this technique has been applied to study the spatio-kinematical distribution of water masers around YSOs are Cepheus A, W75N (Torrelles et al. 1996, 1997), and AFGL 2591 (Trinidad et al. 2000).

3. VLBI PROPER MOTION STUDIES OF MASERS

In both scenarios, either if the masers are tracing disks or outflows, proper motions are expected. In fact, masers participating of the rotating motions of the disks or within outflows moving at velocities >10 km s^{-1} will result in proper motions >0.4 mas/month for a source at a distance of 500 pc. These proper motions are detectable through Very Long Baseline Interferometry (VLBI) multiepoch observations. Although VLBI measurements of proper motions of water masers have been already used successfully to make important contributions in astronomy, including a way to measure distances (e.g., Orion, Galactic Center; Genzel et al. 1981; Reid et al. 1988) and extremely tight constrains on the mass of supermassive black holes in extragalactic nuclei (NGC4258; Miyoshi et al. 1995), this powerful technique is just starting to be applied, in an extended way, to the study of YSOs. The power of this technique was evidenced by the measure of the proper motions of more than 20 H_2O maser spots around the W3(OH)-TW object, revealing a bipolar outflow emanating from this YSO (Alcolea et al. 1992; see also Wilner et al. 1999). These VLBI observations of water masers represent an improvement of angular resolution of two orders of magnitude with respect to the best angular resolution achieved with the VLA in its A configuration.

One of the main goals of the VLBI multiepoch observations toward YSOs is to observe as close as possible the central engine of the "disk-YSO-outflow" system responsible for the phenomena associated with the star formation. In particular, these observations allow us to obtain the full motions (line-of-sight plus tangential velocities) of the associated disk/outflow at scales of AU, setting limits to the relative contributions of rotation and radial motions (inward or outward) in the disks, to know the degree of collimation of the outflow at distances of a few

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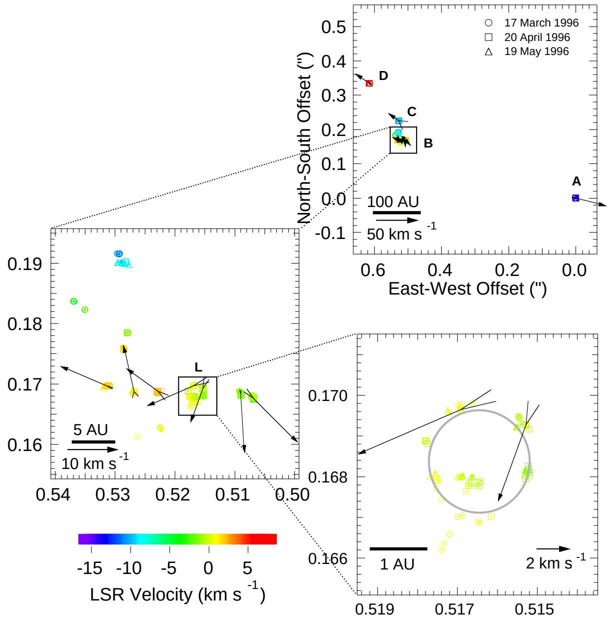

Fig. 3. Water masers and proper motions in IRAS 21391+5802. NOTE: THIS FIGURE IS AVAILABLE IN COLOR IN THE ELECTRONIC VERSION OF THIS ARTICLE, OBTAINABLE FROM `http://www.astroscu.unam.mx/~rmaa/`.

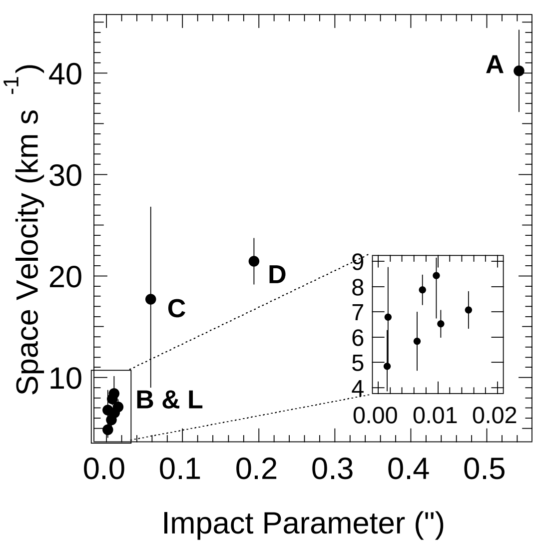

Fig. 4. Variation of the three-dimensional velocity of water masers in IRAS 21391+5802 as a function of distance from the position of the YSO (figure adapted from Patel et al. 2000).

AU, as well as its acceleration and dynamical scales. All these are very exciting perspectives in the understanding of the the star-forming processes.

3.1. *IRAS 21391+5802*

Although the number of YSO sources where this technique has been successfully applied to measure proper motions is still very scarce, the results obtained are already very promising for future and more extended studies toward other sources. This is, for example, the case of IRAS 21391+5802, an intermediate mass star of 3 $M_\odot$. VLBA multiepoch water maser observations carried out by Patel et al. (2000) show a bipolar outflow extended over 500 AU, with a maximum value of the total (3-D) velocity (derived from the line-of-sight velocity and proper motions) of $\sim$ 40 km s^{-1} (Figure 3). The bipolarity of the outflow is observed down to scales of 10–20 AU. Most interesting is the presence of a circular loop of masers of 1 AU radius with low velocity (a few km s^{-1}) around the central source (Fig. 3). This loop of masers is interpreted by these authors in terms of a wind shell. This implies that at small scales (a few AUs) the outflow in IRAS 21391+5802 is poorly collimated, but it is highly collimated far from the star itself, at distances $\geq$ 10 AU. Furthermore, analyzing the motions of the masers in this source as a function of the distance, Patel and collaborators find that the water masers that are more distant from the YSO move faster than the closer ones (see Figure 4). This could be interpreted in terms of acceleration of the gas from distances of 10 AU up to 500 AU. In addition, a short dynamical age, $<$ 40 years, is obtained for the outflow. All these results provide important observational constraints not only for the excitation of the water masers but also for the collimation mechanism of the outflow.

3.2. *S106 FIR*

Another important example is S106 FIR, an intermediate-mass Class 0 protostar, where Furuya et al. (1999; 2000), through VLBA multiepoch water maser observations found a bipolar outflow of 50 AU in size, with signs of acceleration up to distances of 25 AU. They also detected a micro bow-shock structure of 5 AU size at the head of the blueshifted side of the bipolar outflow, traveling at velocities of $\simeq$ 35 km s^{-1} (Furuya et al. 2000), resembling, at a much smaller scale, that of a bow-shock commonly found in association with HH objects and optical jets (e.g., Raga 1995). Both the lack of an associated large-scale molecular outflow and the short dynamical age of the compact water maser bipolar outflow ($\sim$ 900 yr) suggest that the protostar S106 FIR is at a very early stage of evolution (Furuya et al. 2000).

3.3. *Cepheus A*

VLBA multiepoch water maser observations have been also obtained toward the high-mass star forming region of Cepheus A (Torrelles et al. 2001). These VLBA data reveal that some of the individual masers detected previously with the VLA (Torrelles et al. 1996, 1998b) unfold into remarkable filament/arcuate continuous microstructures with sizes from ~ 0.4 AU to 70 AU, all of them signatures of flattened shock surfaces. However, the detailed physical processes that produce these microstructures of masers are not well known, deserving further theoretical studies. Both the morphology and the observed proper motions found in these microstructures imply three different centers of activity in a region of $\sim 0\farcs3$ radius ($\sim$ 200 AU). One of these centers is related to the well known radio-continuum jet Cepheus A HW2 (Rodríguez et al. 1994). For this source, the VLBA data suggest the presence of a wide angle wind ($\sim 130^\circ$) associated with the central object at distances of 150 AU. In the other two centers of activity there is no known embedded source, suggesting that these hypothetical YSOs must be in their very earliest stages of evolution.

4. CONCLUSIONS

Herbig-Haro (HH) objects, jets, molecular outflows, and masers, are all of them signatures of the mass ejection phase related with the first stages in the evolution of YSOs. According to theory, all these phenomena require the formation of a "disk-YSO-outflow" system to account for the observed properties. However, the observational study of these systems has serious instrumental limitations, mainly due to the high angular resolution and sensitivity required. Interferometric maser observations of several molecular species (e.g., H_2O, OH, CH_3OH) provide a very powerful tool to study with high angular resolution the gas close to the YSOs. In this way groups of masers have been found to be associated with radio-continuum jet sources. In some cases, masers seem to be distributed in a band perpendicular to the central radio-continuum jet, as might be expected for accretion disks. In other cases, masers seem to be distributed along the jet source, consistent with being part of the outflow. Recently, a new way to study these star-forming regions through VLBI measurements of proper motions of the associated masers has emerged. These observations are just starting to reveal exciting perspectives, such as measuring the full motions of the gas within the circumstellar disks/outflows at scales of AU, discovering new phenomena, and opening new, still puzzling questions.

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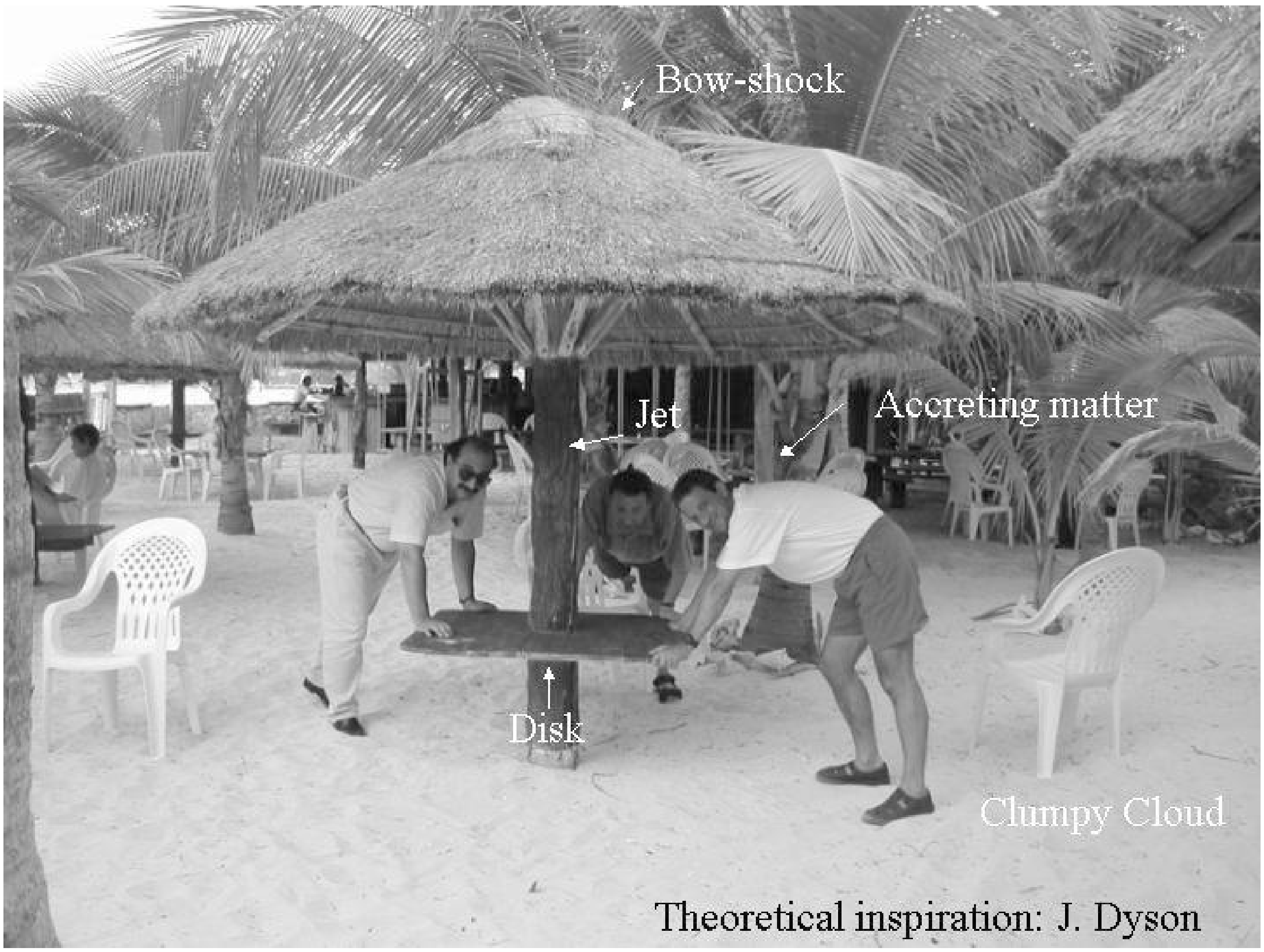

Luis Miranda, José María Torrelles, & Jorge Cantó reenact the star formation process.
(Photo and annotations: J. A. López.)

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