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SEARCH FOR PROTOPLANETARY DISKS WITH MOLECULAR LINE OBSERVATIONS

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RESUMEN

Quizás el descubrimiento observacional más importante de los últimos 20 años relacionado con la formación estelar haya sido el constatar que las primeras etapas de evolución de las estrellas están caracterizadas por grandes eyecciones de masa en forma de vientos supersónicos, la mayoría de ellos bipolares. Los modelos teóricos sobre formación estelar predicen la presencia de discos en torno a estrellas jóvenes, que además parecen ser necesarios para la generación y colimación de los vientos bipolares. En este trabajo resumimos brevemente los esfuerzos encaminados hasta ahora a cartografiar esos discos con líneas moleculares, poniendo un énfasis especial en las expectativas que se tienen en resolver, tanto espacial como cinemáticamente, discos protoplanetarios de tamaños del orden de 100 UA con la nueva generación de interferómetros que se espera entren en funcionamiento a principios del siglo XXI.

ABSTRACT

Perhaps the most important observational discovery related to star formation in the last 20 years has been to realize that the early stages of stellar evolution are characterized by energetic mass outflows by means of supersonic jets, most of them bipolar. Theoretical models of star formation predict the presence of disks, which also seem to be necessary to create and collimate bipolar winds. In this work, we summarize the efforts directed to map these disks with molecular lines, stressing on our expectations to resolve (both spatially and kinematically) protoplanetary disks of ~ 100 AU of size, using the new generation of interferometers that are expected to operate at the beginning of the 21st century.

Key words: **ACCRETION, ACCRETION DISKS — ISM–JETS AND OUTFLOWS — STARS–FORMATION**

1. INTRODUCTION

As long ago as the middle of the eighteenth century, the philosopher Inmanuel Kant and the mathematician Pierre-Simon Laplace independently proposed the idea that our Solar System was formed from a cloud of gas and dust in slow rotation that collapsed by its own gravitational force, and created in its inner parts a spinning disk, giving then rise to the Sun and the planets. However, although this idea has always been in the astronomers' minds to explain the birth of other stars, disks were practically ignored until recently as important components of young stellar object (YSO) systems to explain their related phenomena and physical parameters. So, what happened in the last 10-20 years to produce in the astronomical community such an enormous interest to study theoretically and observationally disks around YSOs? Without doubt, one of the main causes for that sudden interest can be found in the realization that the earliest stages of the YSOs are characterized by outflows (usually very collimated) that are coeval with the accretion phase, although a detailed and accepted theoretical model has yet to be produced. These outflows are observed as a variety of phenomena such as Herbig-Haro (HH) objects, supersonic molecular outflows (most of them bipolar; Rodríguez et al. 1982), thermal jets (Mundt & Fried 1983), and high-velocity masers (Elitzur 1995). According to theory, most of these phenomena require the presence of disks around the YSOs, playing an important role in the collimation of outflows. This collimation is necessary to provide an efficient mechanism for the excitation of HH objects far from the YSOs (Cantó 1980),

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to explain the bipolarity of molecular outflows (Torrelles et al. 1983), and to produce jets (Mundt & Fried 1983). This has motivated astronomers to search and study molecular disks of different physical sizes around YSOs. In this sense, at the beginning of the 80's, it was found that at the centers of the bipolar outflows there are high-density molecular cores elongated perpendicular to the direction of the outflows. These structures were interpreted as interstellar toroids playing an important role in the collimation of bipolar outflows at scales of 0.1 pc (Torrelles et al. 1983). On the other hand, the detection of thermal jets showed that winds from YSOs are already collimated at scales of a few hundreds of AU, which requires the presence of circumstellar disks (Mundt & Fried 1983). Consequently, it seems that the star formation processes have originated several flattened molecular structures surrounding YSOs, with sizes ranging from ~ 0.1 pc (interstellar toroids) to 100 AU (protoplanetary disks) (e.g., HH1-2, Torrelles, Gómez, & Anglada 1995; see Rodríguez 1988 for a review).

This way, a scenario has emerged in which stars form by a gravitational inside-out collapse of molecular cores of sizes ~ 0.1 pc and temperatures ~ 10 K, producing in their inner parts an accretion disk in Keplerian rotation and dimensions $\lesssim$ 1000 AU (protoplanetary disks). It is thought that a significant fraction of the accreting material is magnetically accelerated from the surface of the circumstellar accretion disk in the form of a bipolar wind. These winds would remove angular momentum from the protostar-disk system, preventing the protostar from rotating faster than its breakup speed, and allowing it to accrete disk material. In addition, winds generate the outflow phenomena mentioned above and have an important influence in the future evolution of the parental molecular clouds (see, e.g., Lizano & Torrelles 1995).

2. OBSERVATIONAL EVIDENCE FOR THE EXISTENCE OF PROTOPLANETARY DISKS

Before presenting the observational evidence for the existence of protoplanetary disks around YSOs, we should mention that at the moment there is no conclusive image of a protoplanetary disk with a size of a few hundred of AU showing both its spatial and kinematical distributions. The main limitation to obtain it is a combination of sensitivity and angular resolution requirements for the data. In this sense, to resolve disks of 100 AU at 100 pc distance (the distance of the closest star-forming sites), an angular resolution better than $1''$ is needed. Given the relatively low temperatures of ~ 100 K expected in protoplanetary disks (Beckwith et al. 1990), the detection and kinematical study of these disks with molecular lines is to be carried out in far-infrared and radio wavelengths. Unfortunately, there is no available observational system that can provide such a high angular resolution at these wavelengths (see §4).

In spite of that limitation, there is a great deal of compelling evidence for such protoplanetary disks to exist in YSO systems. Some of these are:

1. The existence of our solar system, which seems to have formed from a disk.
2. The presence of highly collimated jets around YSOs and their theoretical relationship with disks of 100 AU size. Perhaps, the most spectacular example of a jet-disk system is HH 30, recently reported by Burrows, Stapelfeldt, & Watson (1996) using the Wide Field Planetary Camera (WFPC) of the NASA/ESA *Hubble Space Telescope* (*HST*). The *HST* images show a bipolar jet emerging perpendicular to a "*dust disk*" that is obscuring the light from the star (see Fig. 1a). These authors interpret their images as an accretion disk of a few hundred of AU, whose spatial thickness increases with distance to the central stellar object.
3. Most stars in their earliest stages of evolution undergo the outflow phase (Rodríguez 1990) and, according to theory, disks of a few hundred of AU are necessary to produce the outflows.
4. In some pre-main sequence stars (PMS), forbidden lines from atomic winds are predominantly blueshifted. This has been taken as an indication that the receding part of the wind is obscured by a disk of ~ 100 AU (Edwards et al. 1987).
5. The spectral energy distribution (SED) in YSOs in the range $0.5 \lesssim \lambda \lesssim 300$ μm can be explained by the presence of collapsing flattened structures (Calvet 1995).
6. From millimeter continuum observations of PMS, extinctions $A_V \simeq 10^3$ mag are estimated toward these objects. Since some of them are optically visible, it has been suggested that the millimeter emission comes from flattened dust structures (e.g., disks with $M_D \simeq 0.01$ $M_\odot$) around these PMS (Beckwith et al. 1990).

In what remains of this paper we concentrate in the evidence and expectations of molecular line observations with high angular resolution.

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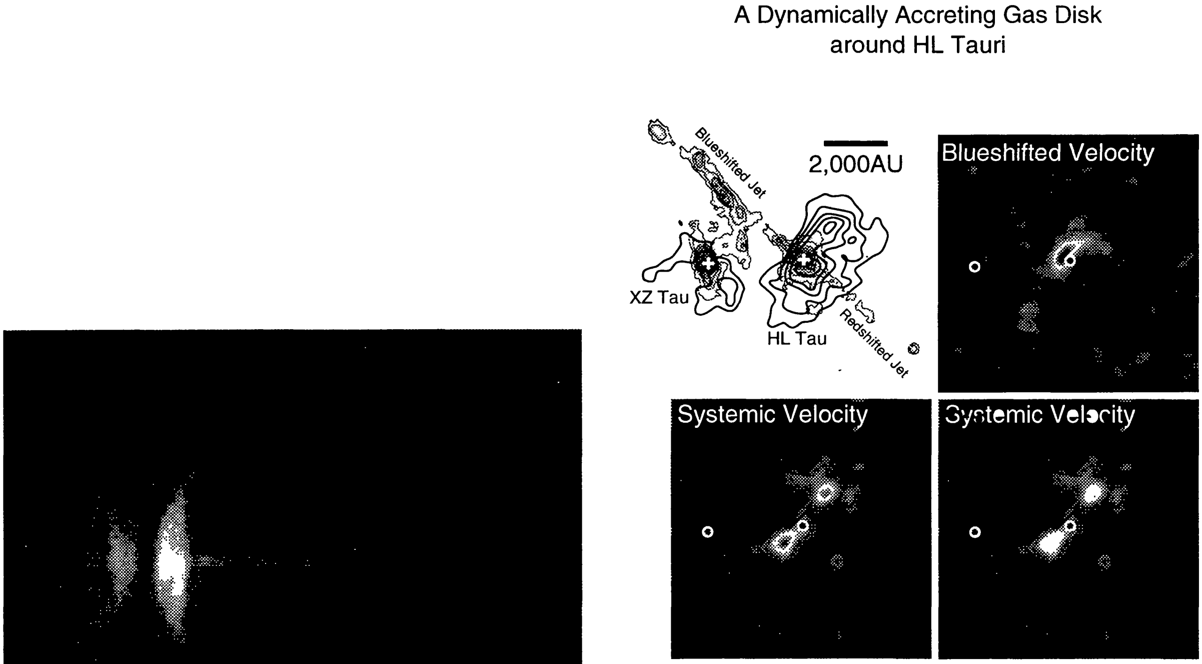

Top Left:	Integrated intensity map of ^{13}CO (J=1–0) superimposed on the optical jet observed by Mundt et al. (1988)
Top Right:	^{13}CO map for blueshifted velocity
Bottom Left:	^{13}CO map for systemic velocity
Bottom Right:	^{13}CO map for redshifted velocity

Fig. 1. (a; left panel) Disk and jet in HH 30. The scale bar represents 1000 AU (courtesy of Burrows, Stapelfeldt, & Watson 1996, and the WFPC2 Science Team of the *HST*); (b; right panel) ^{13}CO maps of HL Tau (from Hayashi, Ohashi, & Miyama 1993).

3. MOLECULAR LINE OBSERVATIONS WITH HIGH ANGULAR RESOLUTION

Molecular line observations are considered as an important tool to detect and study protoplanetary disks. With this kind of observations we could identify the spatial distribution of the gas as well as its kinematics and temperature profile, all of these necessary to know the physical conditions in the disks before planets form. This justifies the huge effort directed to detect these disks around both low (e.g., HL Tau, HH1-2) and high (e.g., Orion-KL IRc2, Cepheus A HW2) mass stars using molecular line observations.

3.1. Low Mass Stars: HL Tau

One of the better studied low-mass star systems is HL Tau. Hayashi, Ohashi, & Miyama (1993), through ^{13}CO(J=1-0) observations with $\sim 5''$ resolution ($\sim$ 750 AU to the distance of HL Tau) have confirmed the presence of a molecular disk (first detected by Sargent & Beckwith 1991) elongated perpendicular to the optical jet in the region (Mundt, Ray, & Burke 1988). The mass and radius of this disk are 0.03 $M_\odot$ and 1400 AU, respectively. Although the size of this disk is an order of magnitude larger than that expected in protoplanetary disks, it has originated a great deal of controversy, in particular about its kinematics. For instance, Hayashi et al. (1993) show that the largest velocity gradients lie along the minor axis of the disk. Using the argument that the molecular disk is perpendicular to the optical jet, which is blueshifted toward the northeast, these authors conclude that the southwestern part of the disk is in the foreground. Since this part of the disk is redshifted with respect to its northeastern part, Hayashi et al. (1993) conclude that the disk is contracting, with $\dot{M}_{acc} \simeq 10^{-5}$ $M_\odot$ yr^{-1} (Fig. 1b). This kind of argumentation has also been used to conclude that in the HH1-2 region there is a molecular toroid of 0.1 pc size with contracting motions around the radio source VLA 1 (Torrelles et al. 1995). More recently, Cabrit et al. (1995) have presented new ^{13}CO observations with higher angular

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1996RMxAC...4...13T

resolution (~ 3″) toward HL Tau, showing that not all the kinematics of the molecular disk can be explained by contracting motions, but that there must be outflow motions as well. A plausible scenario emerging now in HL Tau is that the ~ 2000 AU molecular structure observed in ^{13}CO represents a flattened infalling outer envelope from which an smaller protoplanetary disk of ~ 100 AU size (still undetected) takes mass (Hartmann 1994).

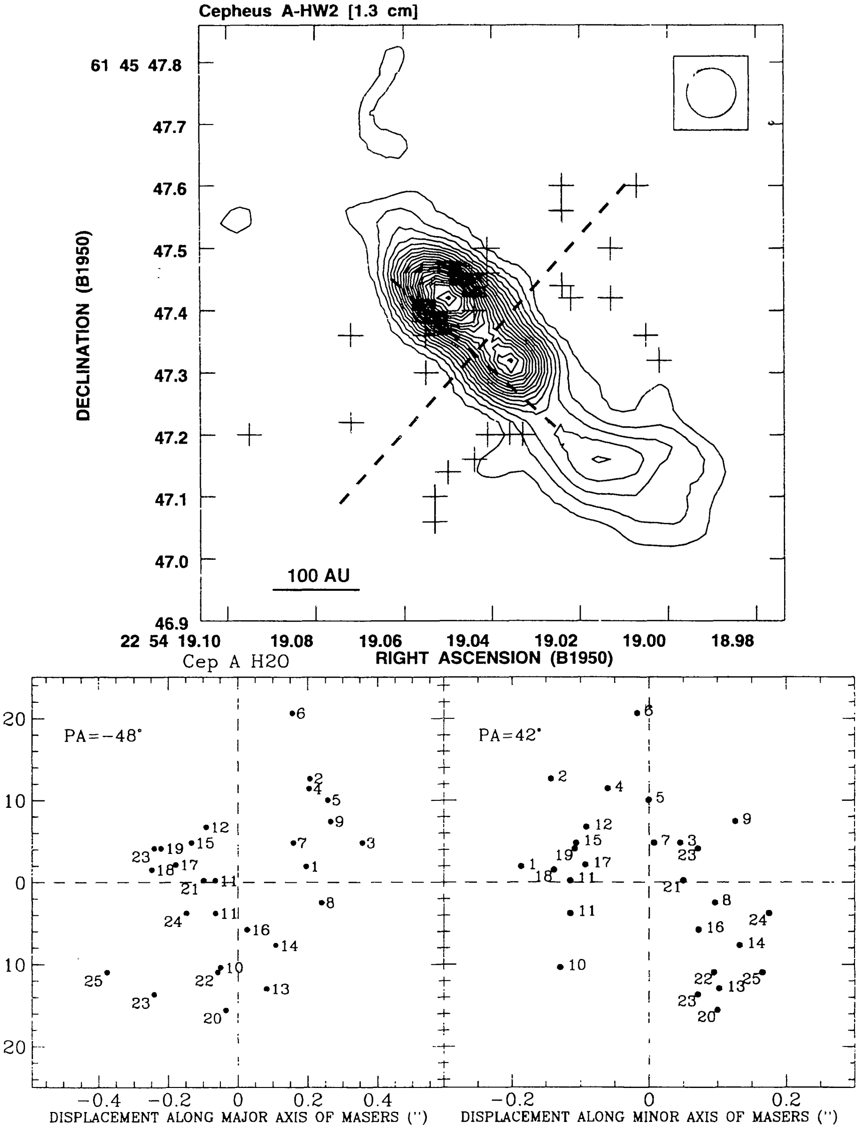

Fig. 2. (a; top) Contour map of the 1.3 cm continuum emission of the Cepheus A HW2 thermal biconical jet. Crosses indicate the position of the H_2O maser spots. Dashed lines indicate the major and minor axes of the disk traced by the maser spots. (b; bottom) Position-velocity distribution of the H_2O maser spots. The vertical axis corresponds to the velocity of the maser spots after subtracting their systemic velocity (-11.7 km s^{-1}). The horizontal axis corresponds to the relative position of the maser spots along the major (bottom left) and minor (bottom right) axis of the maser distribution with respect to their geometrical center. The spots are numbered according to their right ascension-declination positions in Fig 2a (top). The velocity gradient along the major axis (bottom left) can be interpreted as rotating motions. The velocity gradient along the minor axis (bottom right) can be interpreted as radial motions within the disk. Since the northeast side of the HCO$^+$ bipolar outflow associated with HW2 (Gómez et al. 1996a) is blueshifted, and the southwestern side is redshifted, the redshifted motions in the southwestern side of the disk and the blueshifted motions of the northeastern side of the disk (see right panel) are then consistent with contracting motions (from Torrelles et al. 1996).

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1996RMxAC...4...13T

3.2. High Mass Stars: Orion-KL IRc2 and Cepheus A HW2

The detection of HH objects, jets, and bipolar outflows associated with young high-mass stars (e.g., Cepheus A, Garay et al. 1996; HH80-81, Martí, Rodríguez, & Reipurth 1995) has revealed that the collimation phenomenon is not exclusive of low-mass stars, and consequently that young high-mass stars must also be surrounded by disks of sizes $\lesssim$ 1000 AU. However, given that young massive stars are found in molecular clouds that are located at large distances, the detection and study of their associated disks using thermal molecular lines is even more difficult than in the case of low-mass stars. However, strong maser emission of different molecules (e.g., H_2O, SiO, OH) is often observed toward these young massive stars. In a few cases, these masers have been studied with milliarcsecond precision (using radio interferometric techniques), which has revealed spatial and velocity distributions compatible with disk structures. These are, for example, the cases of the luminous ($L \geq 10^4\ L_\odot$) sources of Orion KL IRc2, and Cepheus A HW2.

Orion KL IRc2. Plambeck, Wright, & Carlstrom (1990) and Wright et al. (1996) have mapped the v=1 J=2-1 SiO maser transition around Orion-KL IRc2, modeling their results in terms of a ring of SiO masers of 80 AU diameter originating in a rotating and expanding disk. This disk would be perpendicular to the CO bipolar outflow of the region and parallel to a more extended flattened molecular structure of 1000 AU diameter observed in the v=0 J=2-1 SiO transition. This particular distribution of a disk structure inside another disk structure is reminiscent of that observed in some low-mass star-forming regions.

Cepheus A HW2. Torrelles et al. (1996), using the VLA in the A configuration, measured at 1.3 cm the relative positions of the thermal biconical jet of the massive star Cepheus A HW2 (Rodríguez et al. 1994) and the water maser emission, finding 25 H_2O maser spots mainly distributed in the southeast-northwest direction, i.e., perpendicular to the thermal jet (Fig. 2a). The elongated distribution of the H_2O maser spots as well as the velocity gradients observed along the major and minor axes (Fig. 2b) suggest that the maser emission is tracing a rotating and contracting molecular disk of 300 AU radius. The observed velocity gradients in the maser spots could be gravitationally bound by a central mass of $70\pm40\ M_\odot$. Given that the mass of HW 2 is probably on the order of 20 $M_\odot$, the molecular disk may be self-gravitating.

Finally, Fiebig et al. (1996) have also reported that their H_2O maser observations toward IRAS 00338+6312 (with an intermediate luminosity of $\sim$ 1000 $L_\odot$) indicate a kinematic and spatial pattern expected from a protostellar disk.

4. FUTURE WORK

If we want to obtain a conclusive evidence of the existence of protoplanetary disks and to determine their physical characteristics, we have to detect spatially resolved molecular line emission from these disks. In this sense, the physical conditions of temperature and density expected in protoplanetary disks [$T_K \simeq 100$ K, Beckwith et al. 1990; $n(H_2) \simeq 10^{11}\ cm^{-3}$, Morfill, Tscharnuter, & Völk 1985] are optimum to be studied in (sub-)millimeter wavelengths. For these conditions, it is expected that the gas in the disk emits hundreds of molecular lines. It seems then reasonable to expect that the future instruments working at these wavelengths and providing angular resolutions of tenths of arcsecond (e.g., Millimeter Array [MMA] of the National Radio Astronomy Observatory; Submillimeter Array [SMA] of the Smithsonian Astrophysical Observatory; see Ho 1995 for a description of these and other instruments) can finally resolve protoplanetary disks spatially and kinematically.

Given the importance of molecular line observations, several models of thermal line emission from disks in Keplerian rotation have been developed. Most of these models have been used to compare with presently available observations (Beckwith & Sargent 1993; Omodaka, Kitamura, & Kawazoe 1993), i.e., without resolving the disk structures (beam $\geq 1''$), and mainly for the emission of CO isotopes at $\lambda \simeq 3$ mm. They predict double-peaked line profiles that are consistent with existing observations. More recently, Gómez & D'Alessio (1995) and Gómez et al. (1996b) have addressed whether protoplanetary disks of $r \simeq 100$ AU can be detected and resolved spatially in different molecular lines when the new interferometers like the MMA and the SMA are operating. These models consider a detailed vertical structure of temperature and density for the disks, which fits the spectral energy distributions from continuum observations of T Tauri stars. Although the particular numerical results strongly depend on factors like the inclination angle and the dust emissivity coefficient, it seems that the detection of resolved protoplanetary disks will be very likely with reasonable integration times. Thus, in the near future we will have new and wide possibilities to systematically study protoplanetary disks (and therefore, their associated mass outflows), and to answer important open questions like:

1. Are these disks in Keplerian rotation? What are their velocity fields?

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2. What are their temperature profiles? $T(r) \sim r^{-3/4}$ (as suggested by disk models that assume accretion and/or heating by a central star), or $T(r) \sim r^{-1/2}$ (as suggested by the SED of YSOs)?

3. What is the evolution of these disks like? How do gas and dust evolve?

They all are crucial questions to know the physical conditions of disks and to answer when planetary systems may form. In this way, Dutkewich (1995), with near-infrared continuum observations of old pre-main sequence and young main-sequence cluster stars shows that there is no infrared excess after an age of $\sim 3\times10^6$ yr, concluding that at that time planets must have formed. Since cold dust emits significantly at (sub)–millimeter wavelengths, we can expect that future observations with subarcsecond angular resolution at these wavelengths will allow us to follow the dust evolution in protoplanetary disks.

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