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SUBARCSECOND OBSERVATIONS OF RADIO CONTINUUM FROM JETS AND DISKS

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RESUMEN

En la región centimétrica, el continuo de radio proveniente de estrellas jóvenes está dominado por la emisión libre-libre de los flujos expansivos ionizados y colimados (chorros térmicos), mientras que en la región milimétrica el mecanismo dominante es la emisión del polvo de los discos protoplanetarios. En los últimos años han habido grandes avances en el estudio en radio de los chorros térmicos que incluyen la detección de un chorro unipolar (HH 111), las observaciones de movimientos propios con velocidades del orden de 1,000 km s^{-1} y la eyección de nuevas condensaciones en el sistema masivo HH 80-81, casos de chorros compactos que no están alineados con los chorros ópticos extendidos (HL Tau), y un poderoso chorro con densidad de flujo y tamaño angular escalándose con la frecuencia como predicen los modelos más sencillos (Cep A-HW2). Las observaciones del continuo de radio en longitudes de onda milimétricas se han hecho hasta ahora con resoluciones angulares inferiores al segundo de arco, lo cual no permite el estudio de los tamaños y morfologías de las regiones en las que el polvo emite. Presentamos resultados preliminares de observaciones hechas con el Conjunto Muy Grande ("Very Large Array") de radiotelescopios con resolución angular de 0.3 segundos de arco a 7 milímetros, discutiendo la naturaleza de las fuentes detectadas.

ABSTRACT

At centimeter wavelengths the continuum emission from young stellar objects is dominated by free-free emission from ionized, collimated outflows (thermal jets), while at millimeter wavelengths the dominant mechanism is emission from dust in the protoplanetary disks. In the last few years there have been major advances in the radio study of thermal jets that include a one-sided jet (HH 111), the observations of 1,000 km s^{-1} proper motions and the ejection of new condensations in the massive system HH80-81, compact radio jets that do not align with the more extended optical jets (HL Tau), and a powerful jet with flux density and major angular size that vary with frequency as expected theoretically for the simplest model (Cep A-HW2). The observations of radio continuum at millimeter wavelengths have been made until recently with angular resolutions poorer than one arc sec that do not allow the study of the sizes and morphologies of the emitting dust regions. Preliminary results from observations made with the Very Large Array at 7 millimeters and an angular resolution of 0.3 arc sec are presented and the nature of the sources detected is discussed.

Key words: **ISM: JETS AND OUTFLOWS — STARS: FORMATION — STARS: MASS LOSS — RADIO CONTINUUM: STARS**

1. INTRODUCTION

A major development in the field of star formation that took place during the last decade has been the realization that infall and outflow, two processes once believed to be antagonistic, could coexist in the same object and may actually have a symbiotic relationship. Although a generally accepted model for this situation with simultaneous infall and outflow has yet to be produced, current notions are consistent with young stars having a protoplanetary disk in Keplerian rotation with dimensions of order 100 AU. Part of the rotational energy of this disk, most probably via a magnetohydrodynamic mechanism, is used to power the collimated jets that in its turn give rise to the bipolar outflows and Herbig-Haro objects. In return, the jet may carry away angular momentum, alleviating the well-known problem of excess angular momentum in the system.

Despite major observational advances obtained from low angular resolution studies, it appears clear that a deep understanding of disks and jets in young stars will only be achieved with subarcsecond observations of these objects (equivalent to tens of AUs at the distance of the closest regions of low-mass star formation), since it is at these scales that the protoplanetary disks are expected to become angularly resolved and over which jet acceleration and collimation may be taking place.

In this paper, I review some recent results obtained with subarcsecond angular resolution continuum observations toward young stars at centimeter and millimeter wavelengths. As discussed by Gómez & D'Alessio (1995) in these Proceedings, eventually these subarcsecond observations will have to include spectroscopic capability for a more complete description, but these observations are still in the future. A previous review on disks and outflows is given by Rodríguez (1994). A review of thermal jets from a more general perspective is presented by Anglada (1995) in these Proceedings. Centimeter radio continuum emission is detected not only from the thermal jets very close to the exciting source, but also from the more separated Herbig-Haro objects, and Curiel (1995) has discussed this topic in detail in these Proceedings.

A major problem with the subarcsecond observations of thermal processes is the modest flux density contained in the very small synthesized beam. When observing a source with brightness temperature T_B, at a frequency ν, with a circular beam with angular diameter θ_B, the flux density inside the beam will be given by

$$\left[\frac{S_\nu}{mJy}\right] = 0.40 \left[\frac{\nu}{8.4\ GHz}\right]^2 \left[\frac{T_B}{10^3\ K}\right] \left[\frac{\theta_B}{0.1\ arc\ sec}\right]^2 \qquad (1)$$

This equation implies that very sensitive instruments are required for the study of thermal processes with high angular resolution. For free-free emission, it is expected that $T_B \leq 10^4\ K$, while for thermal emission from dust one usually will have $T_B \leq 10^2\ K$. Most of the observations discussed here were obtained with the Very Large Array (VLA) of the National Radio Astronomy Observatory that with its large collecting area is the most sensitive radio telescope in the 0.1 arc sec scale of angular resolution.

2. SUBARCSECOND OBSERVATIONS OF THERMAL JETS AT CENTIMETER WAVELENGTHS

What is a thermal jet? We can define it as a small ($\leq 1''$) continuum source with elongated morphology and thermal (that is, flat or rising with frequency) spectrum. The thermal jet is expected to be two-sided (bipolar), located at the center of an outflow, and with its major axis well-aligned with the outflow axis, as defined by the presence of Herbig-Haro objects and bipolar molecular outflows on much larger physical scales. In general thermal jets are found in association with low luminosity ($\leq 100\ L_\odot$) sources. Perhaps the best example of this prototypical thermal jet is VLA 1 in the HH1-2 region (Rodríguez et al. 1990). However, departures from these characteristics have been found and in what follows we discuss several sources that have shown to us that the phenomenon is quite diverse.

2.1. The One-Sided Thermal Jet in HH 111

Some of the jets, as observed in the radio, infrared, or optical wavelengths, can show remarkable symmetry in their inner morphology as well as in the sequence of knots that can be detected on both sides of the jet. An example of a symmetric jet on the arc sec scale is HH 80-81 (discussed below). On larger scales (tens of arc sec) jets studied by means of the v=1-0 S(1) line of molecular hydrogen (HH211; McCaughrean, Rayner, & Zinnecker 1994) or millimeter molecular transitions (L1448; Bachiller et al. 1990) can also be quite symmetric.

However, not all jets are symmetric. Using long-slit spectroscopy of forbidden lines, Hirth et al. (1994) have proposed that jets from T Tauri stars can show large differences in the velocities of the redshifted and blueshifted parts of the jet. A more direct evidence for asymmetries in jets is provided by the 3.5 cm VLA map of the jet in HH 111 presented by Rodríguez & Reipurth (1994). As can be seen in Figure 1, on the subarcsecond scale this jet appears to be one-sided.

The ionized gas that emanates from the exciting star and is evident as a protuberance in Figure 1 is very young: assuming a jet velocity of 320 km s^{-1} (Reipurth, Raga, & Heathcote 1992) and a distance of 460 pc, an age of only a few years is derived. The HH 111 energy source is thus at the very moment actively forming the jet. The position angle of the radio jet is 277°±3°. On the other hand, the position angle of the optical jet is 277° (Reipurth & Olberg 1991), so that the radio and optical jets are perfectly aligned.

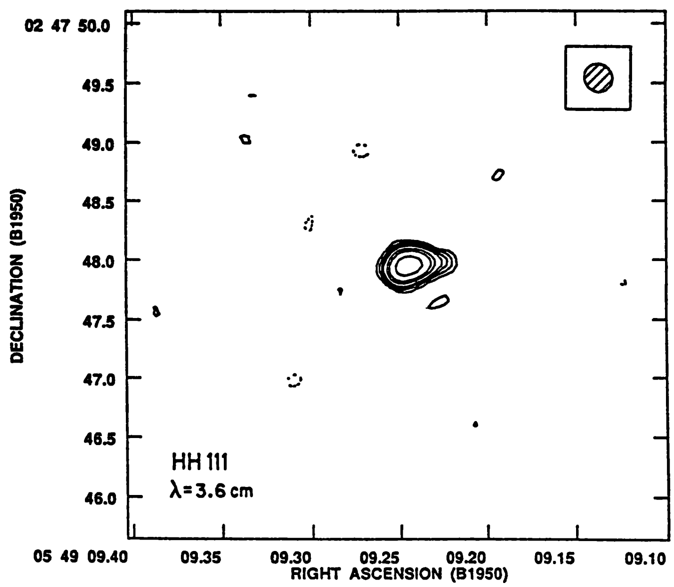

Fig. 1.— Cleaned, natural-weight 3.5-cm VLA-A map of the VLA source at the core of the HH111 system. Contours are −3, 3, 4, 5, 6, 8, 10, and 15 times 20 μJy $beam^{-1}$, the rms noise of the map. The half power contour of the beam is also shown.

Remarkably, while this jet is very asymmetric on the subarcsec scale, it is quite symmetric on larger scales (tens of arc sec). Gredel & Reipurth (1994) find, using [SII] observations, a sequence of five pairs of condensations at very similar distances from the radio core. Further radio observations of the radio jet are needed to establish if phenomena such as flip-flopping could be present on a timescale of years. The possibility that these jets can turn off on one side and on on the other in times of years would imply an extraordinarily dynamical situation in the mechanism that accelerates and collimates the jet. This information could be crucial for all future modeling of the collimated outflow phenomenon in star-forming regions.

HH 111 has still another mistery. The discovery of a molecular hydrogen jet emanating from the VLA source at large angles to the HH 111 jet axis (Gredel & Reipurth 1993) strongly suggests that the source is a binary. VLA observations with higher signal-to-noise ratio are required to see if there is evidence in the radio for a second source. The exciting source of the HH 111 system is extremely obscured (Rodríguez & Reipurth 1994) and the search for an additional star only seems feasible in the radio.

2.2. The Massive System HH 80-81

HH 80-81 are two optically visible Herbig-Haro objects originally discovered by Reipurth & Graham (1988). These objects are located at the edge of the dark molecular cloud L291, a region of recent star formation. They were first detected in the radio by Rodríguez & Reipurth (1989), with centimetric flux densities of a few mJy. These authors also detected the possible driving source of the complex, an object deeply embedded inside the molecular cloud. Its location is coincident with the bright infrared source IRAS 18162−2048. At an estimated distance of 1.7 kpc (Rodríguez et al. 1980; Martí, Rodríguez, & Reipurth, 1993), the luminosity of IRAS 18162−2048 must be as high as $\sim 2 \times 10^4 L_\odot$, suggesting that we are dealing with a very massive young star. The detection of sources of this type indicates that the collimated outflow phenomenon is not restricted to low-mass stars but probably extends to all stellar masses.

HH flows from massive stars are much fewer in numbers than those from low-mass stars, partly because massive stars are, of course, rarer, but also because their evolutionary timescales are much shorter. An estimate of the number of sources similar to the HH 80-81 complex that are expected to exist in the Galaxy can be obtained as follows. Our discussion applies to massive stars, taken to be those with a mass equal or larger than 20 $M_\odot$, corresponding to B0 ZAMS or earlier type. We assume that collimated jets and HH objects can be detected in association with a massive star only before the star reaches the main sequence and produces considerable photoionization of its surroundings. We take this time previous to the main sequence to be of the order of the Kelvin-Helmholtz contraction time, $\tau_{K-H} \simeq GM^2/(RL)$, where G is the constant of gravitation, and M, R, and L are the mass, radius, and luminosity of the star. Since for $M \geq 20\ M_\odot$, $(L/L_\odot) \simeq 3 \times 10^4 (M/20\ M_\odot)^4$ and $(R/R_\odot) \simeq 6(M/20\ M_\odot)$ (Panagia 1973; Allen 1973), we obtain $(\tau_{K-H}/years) \simeq 7 \times 10^4 (M/20\ M_\odot)^{-3}$. On the other hand, the fraction of stars in the IMF more massive than M can be approximated, for $M \geq 20\ M_\odot$, by $F(\geq M) \simeq 8 \times 10^{-4}(M/20\ M_\odot)^{-3}$ (Miller & Scalo 1979) and the total galactic star formation rate is $\dot{N} \sim 4$ stars year^{-1} (Scalo 1986). Then, the number of massive stars with detectable jets is expected to be in the order of $N_{jet} \simeq \tau_{K-H}\ F\ \dot{N} \simeq 2 \times 10^2 (M/20\ M_\odot)^{-6}$. We then expect a few hundred objects similar to the HH 80-81 complex to exist in the Galaxy. Given the steep dependence with stellar mass, only a few jet complexes powered by very luminous stars (O5 or earlier with masses equal or larger than about 40 $M_\odot$) are expected to exist at a given moment in the Galaxy.

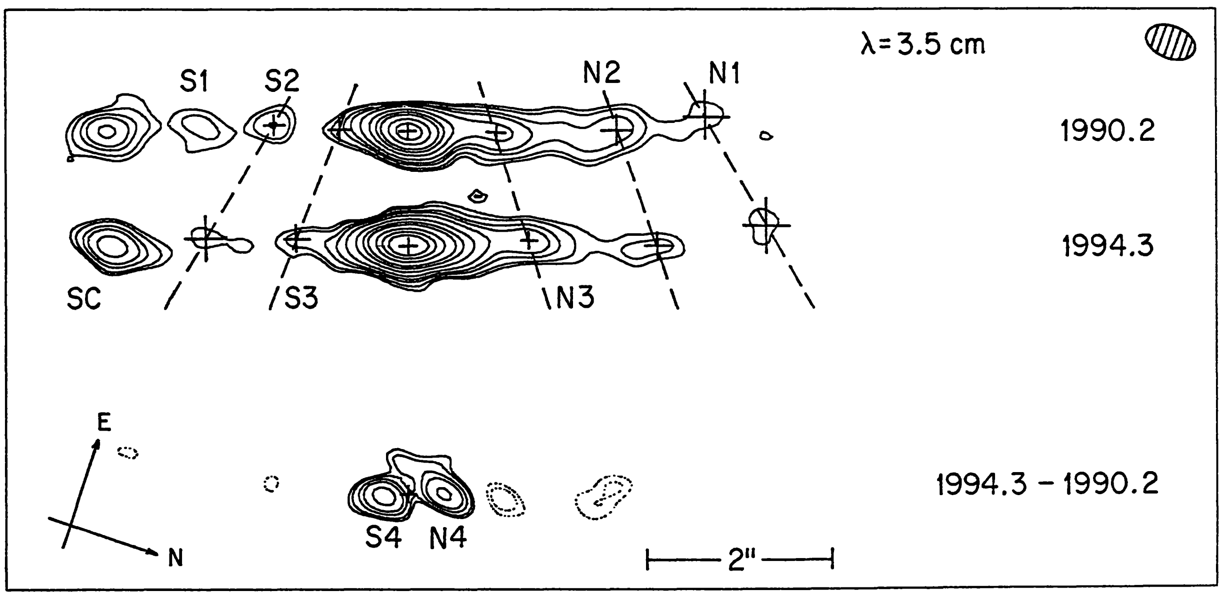

Fig. 2.— Radio maps at 3.5 cm wavelength of the exciting source of the HII 80-81 complex, for the epochs 1990.2 (top) and 1994.3 (middle). The lower panel (bottom) shows the subtraction of the 1990.2 image from that of 1994.3. Several condensations are identified in the two epoch maps and are connected by dashed lines. Their displacement during the 4.1 yr interval is evident. The two newest condensations ejected can only be identified in the subtraction map. The cross at the peak of emission marks the position of the centroid of the core, located at $\alpha(1950) = 18^h16^m12^s.997 \pm 0^s.005$ and $\delta(1950) = -20°48'48''.27 \pm 0''.05$. The outer crosses mark the 2-σ error bars for the position of the condensations with respect to the centroid of the core. The maps have been rotated 110° clockwise to facilitate comparison and the actual orientations of the north and east are shown in the bottom left corner. All maps have been made with the same restoring beam of $0''.47 \times 0''.32$, with position angle of $1^\circ.2$. The beam is shown in the top right corner. Contour levels are -100, -80, -60, -40, -30, -20, -12, -8, -6, -4, -3, 3, 4, 6, 8. 12, 20, 30, 40, 60, 80, 100 times the rms noise of 21, 16 and 26 μJy beam^{-1} for the 1990.2, 1994.3 maps and for the (1994.3$-$1990.2) subtraction map, respectively. The source marked as SC (stationary core) is most probably associated with an independent star.

An extraordinarily well collimated thermal jet was detected by Martí, Rodríguez, & Reipurth (1993) at the core of the system. Second epoch observations made by Martí, Rodríguez, & Reipurth (1995) 4.1 years after the first ones reveal remarkable changes in the jet (see Figure 2). First, large proper motions have been detected in the condensations along the jet. These proper motions are in the range of 70-160 mas yr^{-1}, equivalent to 600 to 1400 km s^{-1} at the distance of 1.7 kpc of the source. Such large velocities have not been previously measured in the context of jets from young stellar objects (where velocities of about 300 km s^{-1} characterize outflow motions from the better studied low-mass stars), and give support to the identification of the powering source of this Herbig-Haro complex as a very massive star (by analogy with what occurs in the stellar winds of main sequence stars).

A second finding by Martí, Rodríguez, & Reipurth (1995) is that between the two epochs of observation an ejection event created two new knots in the jet flow (sources S4 and N4 in the bottom of Figure 2), that in 1994.3 (second epoch observations) appear symmetrically projected at only 500 AU from the central source. The existence of significant clumpiness and symmetry in the jet so close to the star gives support to the notion that disturbances in stellar jets are produced by the driving source, and not as a result of instabilities produced later in the flow.

2.3. HL Tau: A Misaligned Thermal Jet?

In sources such as HH 1-2 (Rodríguez et al. 1990), HH 80-81 (Martí, Rodríguez, & Reipurth 1993), and HH 111 (Rodríguez & Reipurth 1994), the subarcsecond radio jets align within a few degrees with the more extended optical jets and Herbig-Haro objects. There are, however, apparent exceptions to this situation. Perhaps the best documented is HL Tauri. This T Tauri star has a well studied optical jet with a position angle of 45° (Mundt et al. 1990). This result appears to be consistent with the ^{13}CO observations of Sargent & Beckwith (1991) that show an elongated structure aligned nearly perpendicular to the optical jet and interpreted as a Keplerian disk around the star (however, for a review of alternative explanations for the CO observations of HL Tau, see the discussion by Torrelles, Gómez, & Anglada 1995 in these Proceedings).

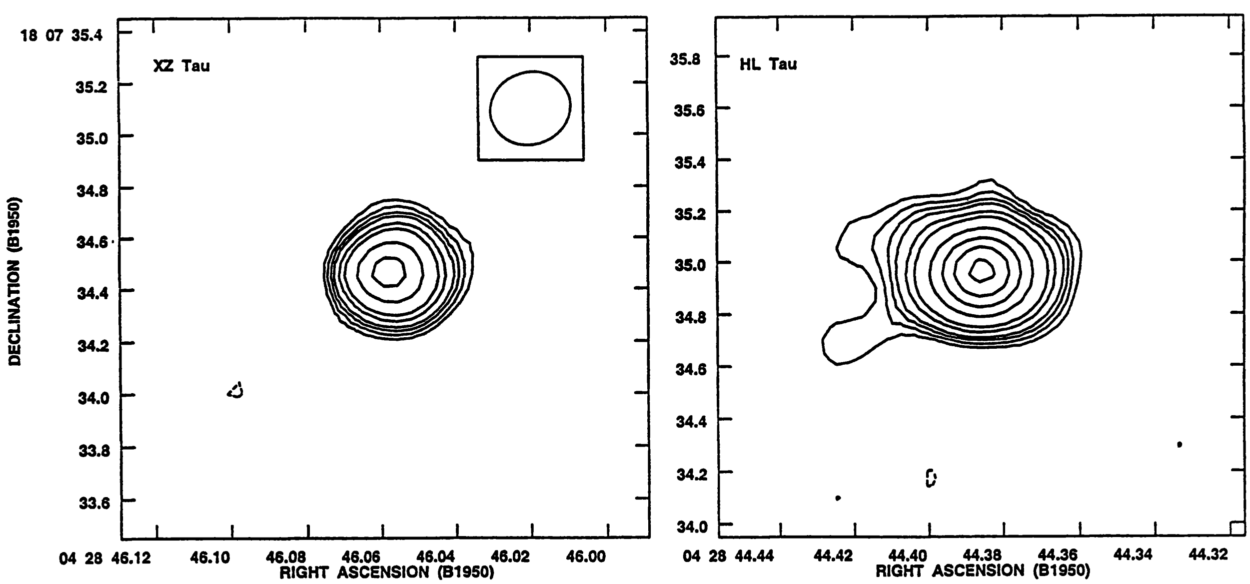

Fig. 3.— Cleaned, natural-weight VLA maps of XZ (left) and HL Tau (right) at 3.5-cm. Contours are −4, −3, 3, 4, 5, 6, 8, 10, 15, 20, 25, and 30 times 9 μJy $beam^{-1}$, the rms noise of the map. The half power contour of the beam is shown in the XZ Tau map. While XZ Tau appears unresolved, HL Tau is elongated in the east-west direction. This elongated structure has been interpreted as a thermal jet by Rodríguez et al. (1994a).

Sensitive, high-resolution VLA observations of the HL Tau region made at 3.5-cm (Rodríguez et al. 1994a) detect HL Tau as well as the nearby young star XZ Tau. While XZ Tau appears unresolved, HL Tau is clearly elongated in the east-west direction. This difference can be seen clearly in Figure 3, where we show both sources side by side and at the same scale. A least squares fit to the HL Tau source gives a deconvolved angular size of

$0''.30 \pm 0''.01 \times 0''.18 \pm 0''.02$, with a position angle of $81° \pm 6°$. By analogy with other elongated radio continuum sources found in the centimeter range in association with young stars, these authors conclude that a plausible explanation for the radio appearance of HL Tau at 3.5-cm is that they are observing a thermal (free-free) radio jet marginally resolved. Furthermore, Rodríguez et al. (1994a) have detected 1.3-cm emission from HL Tau. The VLA observations of HL Tau at 3.5 and 1.3-cm show extended structures associated with this young star that are strikingly different at each wavelength. While the structure observed at 3.5-cm is elongated approximately in the east-west direction (see Figure 3), the 1.3-cm structure is elongated approximately in the north-south direction (see Plate 1 of Rodríguez et al. 1994a). These results were interpreted to imply that while the 3.5-cm emission is dominated by free-free radiation from an ionized outflow, the 1.3-cm emission traces dust emission from a perpendicular, collimating disk.

Although the high angular resolution radio maps at 1.3 and 3.5-cm present a coherent picture at the subarcsec scale, they do not fit well with previously known results on larger angular scales. As mentioned before, the optical jet (Mundt et al. 1990) has a position angle of $\sim 45°$, nearly perpendicular to the major axis of the ^{13}CO structure mapped by Sargent & Beckwith (1991). Possible explanations for this discrepancy might be found in the fact that the optical jet and ^{13}CO disk can be studied only on scales equal or larger than a few arc sec, while the jet and disk detectable in the radio continuum with the VLA are observable within one arc sec from the star. It is possible that the inner part of the disk has suffered a change of angle with time, producing a warped disk structure and a change of angle in the jet. This speculation requires further research.

2.4. Cepheus A-HW2: The Nearly Perfect Jet

With more detailed radio studies, thermal jets should show characteristic dependences with frequency for the total flux density, S_ν, and the deconvolved major axis, θ_{maj}. The theoretical radio continuum spectra of a confined thermal jet has been calculated by Reynolds (1986). For a collimated wind of constant temperature, velocity, and ionization fraction, the flux density and angular dimension of the source depend on frequency as $S_\nu \propto \nu^{1.3-0.7/\epsilon}$ and $\theta_{maj} \propto \nu^{-0.7/\epsilon}$, respectively, where ϵ is the power law index that describes the dependence of the jet half-width, w, (perpendicular to the jet axis) with the distance to the jet origin ($w \propto r^\epsilon$). For the simplest case of a biconical jet (that is, a jet with constant opening angle) one has $\epsilon = 1$ and an expected behavior of $S_\nu \propto \nu^{0.6}$ and $\theta_{maj} \propto \nu^{-0.7}$.

In practice, observational determinations of these spectral dependences are difficult to make and have been possible only in a few source. For HH 1-2, Rodríguez et al. (1990) obtained $S_\nu \propto \nu^{0.3}$ and $\theta_{maj} \propto \nu^{-0.7}$. while for HH 80-81, Martí et al. (1993) find $S_\nu \propto \nu^{0.2}$ and $\theta_{maj} \propto \nu^{-0.3}$. These values are consistent with modified jets as modeled by Reynolds (1986) but are not the simplest case. Thus, it came as a reassuring result for the thermal jet interpretation the finding of Rodríguez et al. (1994b) that the radio source Cep A-HW2 is a thermal jet with $S_\nu = (2.5 \pm 0.3)\ \nu^{(0.69\pm0.06)}$, where S_ν is in mJy and ν is in GHz and $\theta_{maj} = (2.7 \pm 0.1)\ \nu^{(-0.57\pm0.02)}$, where θ_{maj} is in arc sec and ν is in GHz. These power laws are very close to the expected ideal case. A VLA map of this source is shown in Figure 4a and the frequency dependences are shown in Figure 4b.

Since the source seems to fit so well a simple thermal jet model, Rodríguez et al. (1994b) argue that the jet parameters can be derived reliably in this case. From the observations at 8.4 GHz (see Figure 4a) and assuming that the opening angle is approximately given by $\theta_{opening}(radians) = 2\ tan^{-1}(\theta_{minor}/\theta_{major})$, they estimate $\theta_{opening} \simeq 15°$. From the observed flux density and opening angle a relationship between the ionized mass loss-rate, $\dot{M}_w$, and velocity, v_w, of the biconical stellar wind can be derived. Assuming an electron temperature of 10^4 K, a distance of 725 pc, and that the jet axis is nearly perpendicular to the line of sight, they obtain (using eqn.[19] of Reynolds 1986) with ϵ=1) $\dot{M}_{w,-6}\ v_{w,3}^{-1}$=1.1, where $\dot{M}_{w,-6}$ is the mass loss rate in units of $10^{-6}\ M_\odot\ yr^{-1}$ and $v_{w,3}$ is the velocity in units of 10^3 km s^{-1}. Young stars of solar luminosity are known to have wind velocities in the order of a few hundred km s^{-1}. However, an object of intermediate luminosity such as Cep A-HW2 is probably more similar in wind velocity to HH 80-81, for which a velocity of $\sim$700 km s^{-1} is estimated (Heathcote & Reipurth 1995; Martí et al. 1995; see discussion above). Assuming then that the wind velocity is 700 km s^{-1}, a mass loss rate of $8\times10^{-7}\ M_\odot\ yr^{-1}$ is derived. The bolometric luminosity of the region is about $2.5 \times 10^4\ L_\odot$ (Evans et al. 1981). If, following Hughes et al. (1994), one assumes that one half of that luminosity can be attributed to Cep A-HW2, we conclude that the exciting star will be a B0.5 once in the ZAMS, where a mass loss rate of only $\sim 10^{-8}$ is expected (Abbott, Bieging, & Churchwell 1981). Then, at present Cep A HW2 exhibits a mass loss rate about 100 times larger that an object of similar luminosity in the ZAMS. Since it is suspected that winds from young stars can be largely neutral (Lizano et al. 1988), this determination of the ionized mass loss rate should be considered a lower limit to the total mass loss rate. It should be noted, however, that a much lower velocity for the jet will lower the derived ionized mass loss rate.

The momentum rate injected by the jet into the surrounding medium is $\sim 6\times10^{-4}$ $M_\odot$ yr^{-1} km s^{-1}. This momentum rate is similar to the lower limit for the momentum rate of the molecular outflow derived by Rodríguez et al. (1982). Then, it appears possible that the Cep A HW2 jet could be driving the outflow in the frame of unified stellar jet/molecular outflow models such as that of Raga et al. (1993).

Cep A HW2 is then, as HH 80-81, another example that massive, young stars can also drive very collimated outflows.

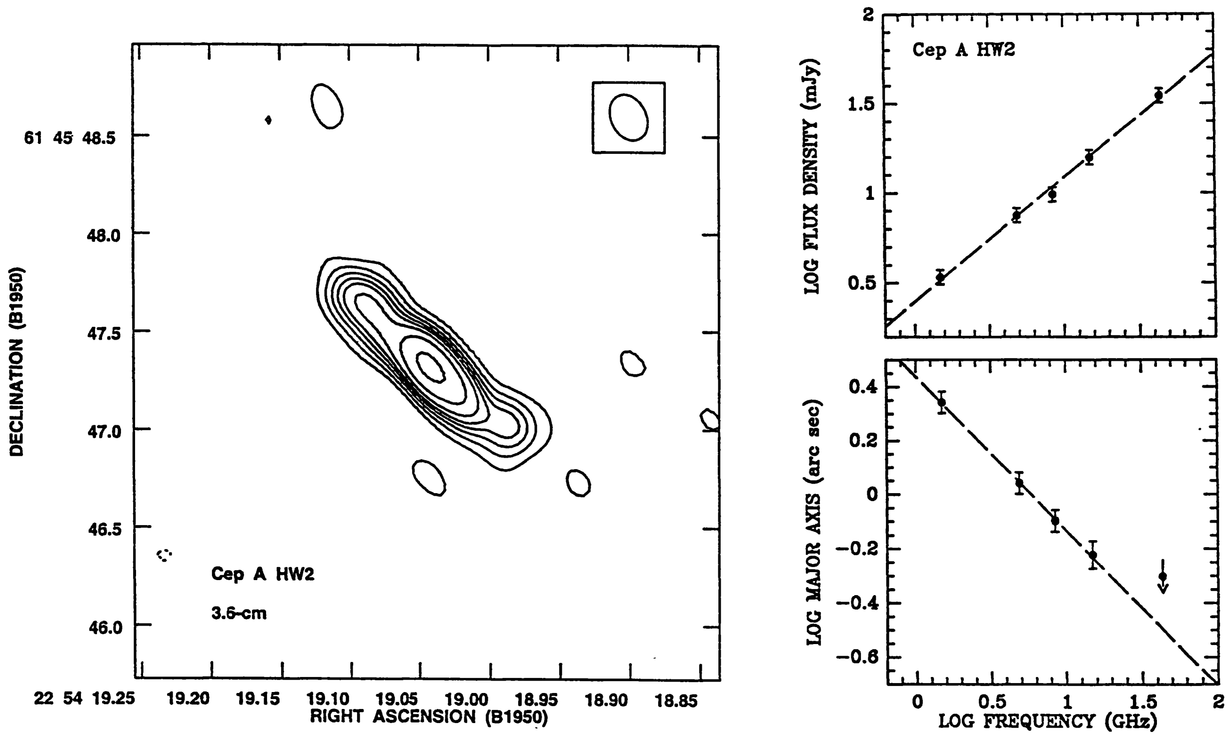

Fig. 4.— (a, left) Cleaned, uniform-weight VLA radio continuum map of Cep A-HW2 at 3.5-cm. Contours are -3, 3, 6, 9, 12, 15, 20, 30, and 50 times 50 μJy beam^{-1}, the rms noise of the map. The half power contour of the beam (0."25 × 0."18, with a position angle of 25°) is shown in the top right corner. (b, right) Flux density (top) and deconvolved major angular axis (bottom) as a function of frequency for Cep A-HW2. The dashed lines are the power-law fits described in the text. At 43.3 GHz the data point for the major angular axis is an upper limit.

3. HIGH ANGULAR RESOLUTION OBSERVATIONS AT 7-mm

For wavelengths shorter than about 1-cm, the continuum emission becomes dominated by thermal emission from optically-thin dust in the protoplanetary disk. With this approach and assuming a mass opacity for the dust it is possible to estimate the total mass in the disk. Beckwith et al. (1990) used the IRAM 30-m radio telescope to observe 1.3-mm emission from a sample of 86 pre-main-sequence stars in the Taurus-Auriga dark clouds. The angular resolution of these observations is 11″. A total of 37 stars (42 % of the sample) were detected. Adopting a mass opacity of $\kappa_\nu = 0.1$ $(\nu/10^{12}\ Hz)$ cm^2 g^{-1}, they derived total disk masses in the range of 0.001 to 1 $M_\odot$ and disk temperatures (at 1 AU from the star) typically in the range of 100 to 200 K. The mass determinations depend crucially on the assumed mass opacity. The issue of the dust opacity in circumstellar disks at millimeter and sub-millimeter wavelengths has been recently discussed by Weintraub, Sandell, & Duncan (1989), Beckwith & Sargent (1991), and Miyake & Nakagawa (1993).

The flux densities of young stars at 1.3-mm are relatively high, reaching as much as about 0.9 Jy in the case of HL Tau. However, the angular resolutions now available at mm wavelengths with interferometers are still in the order of a few arc sec and preclude actual imaging of the disks. Even at the distance of the closest young stars (for example, 140 pc for Taurus), an angular resolution below one arc sec is required. A major advance in the study of the sizes and morphologies of protoplanetary disks has been made by Carlstrom and collaborators, who have used the two-element CSO-JCMT submillimeter interferometer to measure the size and orientation of the disks in HL Tau and L1551-IRS 5.

Our group has followed another approach and as a collaboration between the Very Large Array of NRAO and the Instituto de Astronomía, UNAM, México (with support from CONACyT, México), the ten best antennas of the VLA (selected by holographic techniques) have been equipped with 7-mm receivers. In the first configuration that all of the receivers were available (early 1994 in VLA's configuration A), they were located in the inner antennas of the configuration to achieve resolution of a few tenths of an arc sec. Using the rest of the array at 3.5-cm, a similar resolution is obtained at this band, allowing simultaneous observations of jets (at 3.5-cm) and disks (at 7-mm) at similar angular resolution. This new VLA capability allows mapping of dust emission from possible protoplanetary disks around young stars at 7-mm, where the flux density of the best candidates is estimated to be in the order of 10 mJy. In the continuum mode (four channels of 50 MHz each) at 7-mm the VLA has a sensitivity of 1-σ = 1 mJy in one hour of integration. The same spectral capability existing for the other bands is available at 7-mm and the receivers can tune from about 40 to 50 GHz, reaching also many important atomic and molecular transitions.

At present, the main limitation of the 7-mm system at the VLA is that, for high angular resolution observations, a very stable atmosphere is needed. Of course, when self-calibration is possible this is not a major limitation, but disks at 7-mm are too weak for this phase-correcting technique to be applied.

Until now, we have detected 7-mm emission from DG Tau, Serpens, IRAS 16293-2422B, the central source of HH 80-81 (IRAS 18162-2048), and Cep A-HW2 at levels of 5 to 20 mJy (Rodríguez et al. 1995)

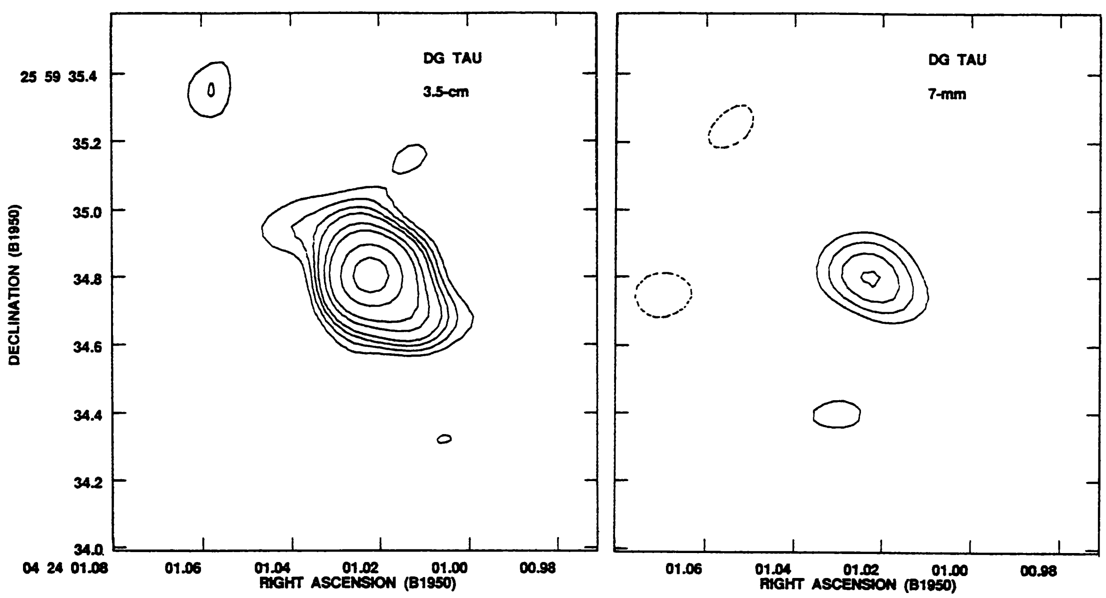

Fig. 5.— Cleaned, natural-weight 3.5-cm (left) and 7-mm (right) VLA maps of DG Tau. Contours are −3, 3, 4, 5, 6, 8, 10, and 15 times 15 (for the 3.5-cm map) and 650 (for the 7-mm map) μJy beam^{-1}, the respective rms noise of the maps. The angular resolution of the observations is about 0.3 arc sec.

In the case of the massive sources (IRAS 18162-2048 and Cep A-HW2), the 7-mm flux density agrees with a power-law extrapolation of the centimeter flux densities, suggesting that in these sources, even at 7-mm, we are still dominated by free-free emission from the jet. In contrast, in the remaining three sources detected the 7-mm emission appears to significantly exceed the value expected from an extrapolation from the centimeter wavelengths, suggesting that emission from dust starts to dominate. In Figure 5 we show the 3.5-cm and 7-mm maps obtained for DG Tau, while in Figure 6 we show the spectrum of this source.

As can be seen in Figure 6, the 7-mm emission exceeds the value expected from the extrapolation of the centimeter observations. The observations of DG Tau pose a puzzle. Using standard models for protoplanetary disks (D'Alessio et al. 1995) one would expect the 7-mm source to have an extension of about one arc sec. However, the observations indicate an unresolved ($\lesssim$0.3 arc sec) source. We can think of two explanations for this result. One is that we are seen at 7-mm a very compact free-free component that is optically thick at longer wavelengths. A problem with this explanation is that the required number of ionizing photons (already difficult to account for in the case of the centimeter observations) become quite large. A second explanation implies a revision of the standard model, so as the compact and relatively bright emission seen at 7-mm can be account for as arising in dust.

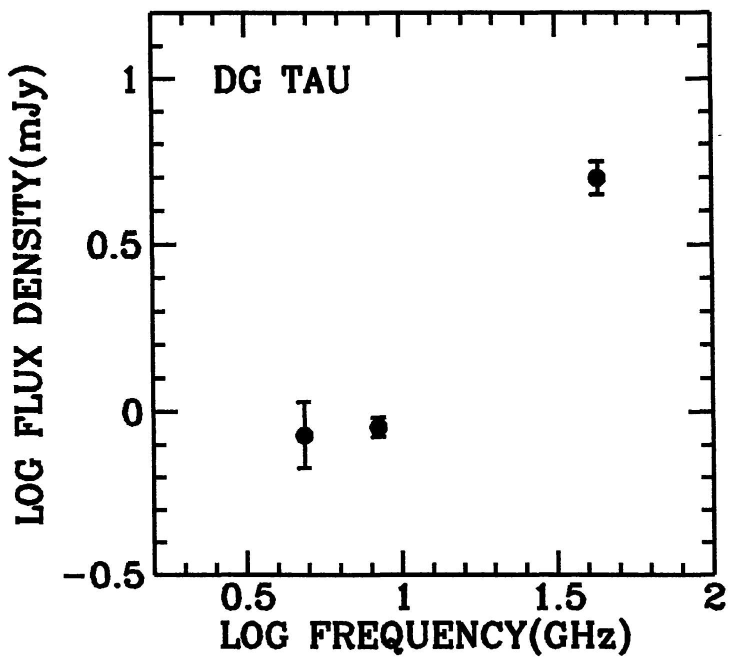

Fig. 6. — Radió spectrum of DG Tau. The 3.5-cm and 7-mm points are from Rodríguez et al. (1995) and the 6-cm point is from Cohen, Bieging, & Schwartz (1982).

We conclude emphasizing that the band of 7-mm will be important in the study of jets and disks. Interestingly, while the opacity of the free-free emission decreases with frequency (as $\nu^{-2.1}$), the opacity of dust emission increases with frequency (about as ν^{+1}). One then concludes that observations around 7-mm, the frequency where the free-free and dust contributions are comparable, will be the ones better suited to penetrate closer to the star. Indeed, as in the case of the thermal jets (whose size decreases with frequency), dust disks may also show a dependence of angular size with frequency, but in this case with the size increasing with frequency. Then, the smallest observable sizes for both disks and jets will occur near 7-mm.

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