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Dust and CO in the T Tauri Circumstellar Matter

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We present sub–arcsecond resolution observations of gas and dust around T Tauri in order to try to discriminate between several components in the circumstellar material. Observations with the Owens Valley Millimeter array at 267 GHz reveal continuum emission, as well as — on the short baselines — HCO^+ J=3→2 emission. Submillimeter interferometer data between the CSO and JCMT were taken at 357 GHz.

The continuum emission indicates an unresolved component (70 AU) at the position of T Tau N, but no trace of a second component (T Tau S) is found. Comparing with single dish data, considerable amounts of gas and dust is inferred to be present on a larger, circumbinary, scale of $\approx$ 1000 AU. Preliminary estimates indicate a relatively low CO to dust ratio in the circumbinary envelope.

INTRODUCTION

The circumstellar material around T Tau shows complicated structure at different scales and different observing frequencies. This is partly due to the fact that the optical star (T Tau N) is accompanied by a close infrared companion (T Tau S) (Ghez et al. 1991). Furthermore, much of the action appears confused, since the rotation axis is probably close to the line of sight. This makes it difficult to resolve outflow components and to detect the kinematic signature of rotation, for instance in a circumstellar disk.

Here we present sub–arcsecond resolution observations of gas and dust to try to discriminate between several components. How much matter is still in a common envelope around the young binary? Can we discriminate between circumbinary and (multiple) circumstellar disks?

An indication that a circumbinary envelope is still present comes from our observation that HCO^+ J=1→0 and CS J=2→1 emission is extended when mapped with the OVRO $5''$ – $7''$ beam. In HCO^+ J=1→0 a red–shifted self–absorption feature is present, which is not observed at higher HCO^+ transitions, indicating that low rate accretion from this envelope may still continue. Furthermore, Calvet et al. (1994) model T Tau infrared emission in terms of an infalling envelope, where we see the optical star through the cavity blown by the outflow.

Previous observations have revealed many components to be present in the T Tau system. The double star is seen with a separation of $0\farcs73$ and close to north–south (Ghez et al. 1991) . T Tau S is invisible in the optical but appears to be the brighter object at mid–infrared as well as radio wavelengths.

Several outflows are present in the system, both in molecular and ionized gas (Böhm & Solf 1994). The molecular outflow is probably close to the line of sight (Levreault 1988, Van Langevelde et al. 1994*b*). On a much smaller scale there is evidence that we see the optical star almost pole–on ($i = 13°$, Herbst et al. 1986). Previous interferometer observations indicate that circumbinary CO may be seen at a small inclination (e.g. Weintraub et al. 1989*a*).

SUB–ARCSECOND RESOLUTION OBSERVATIONS

In Fig. 1 data obtained with the Owens Valley Millimeter array at 267 GHz are shown. Observations were done on Dec. 1 1994 with 6 telescopes in good conditions. The spectrometer was centered on the HCO^+ J=3→2 transition, continuum data are available from the 1 GHz broad band channel. Although the phase stability and sensitivity are substantially decreased at such high frequency, we are able to detect continuum emission, as well as — on the short baselines — HCO^+ J=3→2 emission. Using robust weighting in the new AIPS task IMAGR, it was possible to obtain sub–arcsecond resolution without giving up much of the sensitivity.

Furthermore, Single Baseline submillimeter Interferometer (SBI) data between the CSO and JCMT were taken at the frequency of HCO^+ J=4→3 at 357 GHz on October 28 1994. The line was not detected, neither in emission, nor in absorption. A $\approx$ 400 mJy compact continuum source is inferred from the observations. This flux is much lower than the 1.2 Jy obtained in a $15\farcs8$ beam by Weintraub et al. (1989*b*). Typical fringe spacing for the SBI is $\lesssim 1''$.

The continuum emission in Fig. 1 appears unresolved. An upper limit for the size of the continuum source is $0\farcs5$, or 70 AU. This is remarkable, since the separation of the two binary components is $0\farcs71$. The data indicates that the compact dust emission is located at T Tau N. We tentatively identify this detection with a $\leq$ 70 AU accretion disk around the optically visible star. The CSO–JCMT detection is consistent with this.

Although it is very bright at other wavelengths there is no trace of dust emission close to T Tau S with an upper limit of 40 mJy at 267 GHz. The source T Tau S is reported to be variable, but its current low state cannot explain the absence of cool optically thin dust emission. This observation yields new clues on the nature of T Tau S. Maybe it is a young object which has not formed an circumstellar disk yet, more likely the vicinity of the more massive T Tau N does not allow the formation of a stable circumstellar disk.

In the 110 GHz continuum data it is impossible to distinguish between T Tau N and

T Tau S (Fig. 3). The center of emission is shifted to the south compared to the 267 GHz map, but the large beam will pick up a contribution from the circumbinary dust, and the mechanism responsible for the T Tau S radio emission cannot be neglected either, as is clear from Fig. 2.

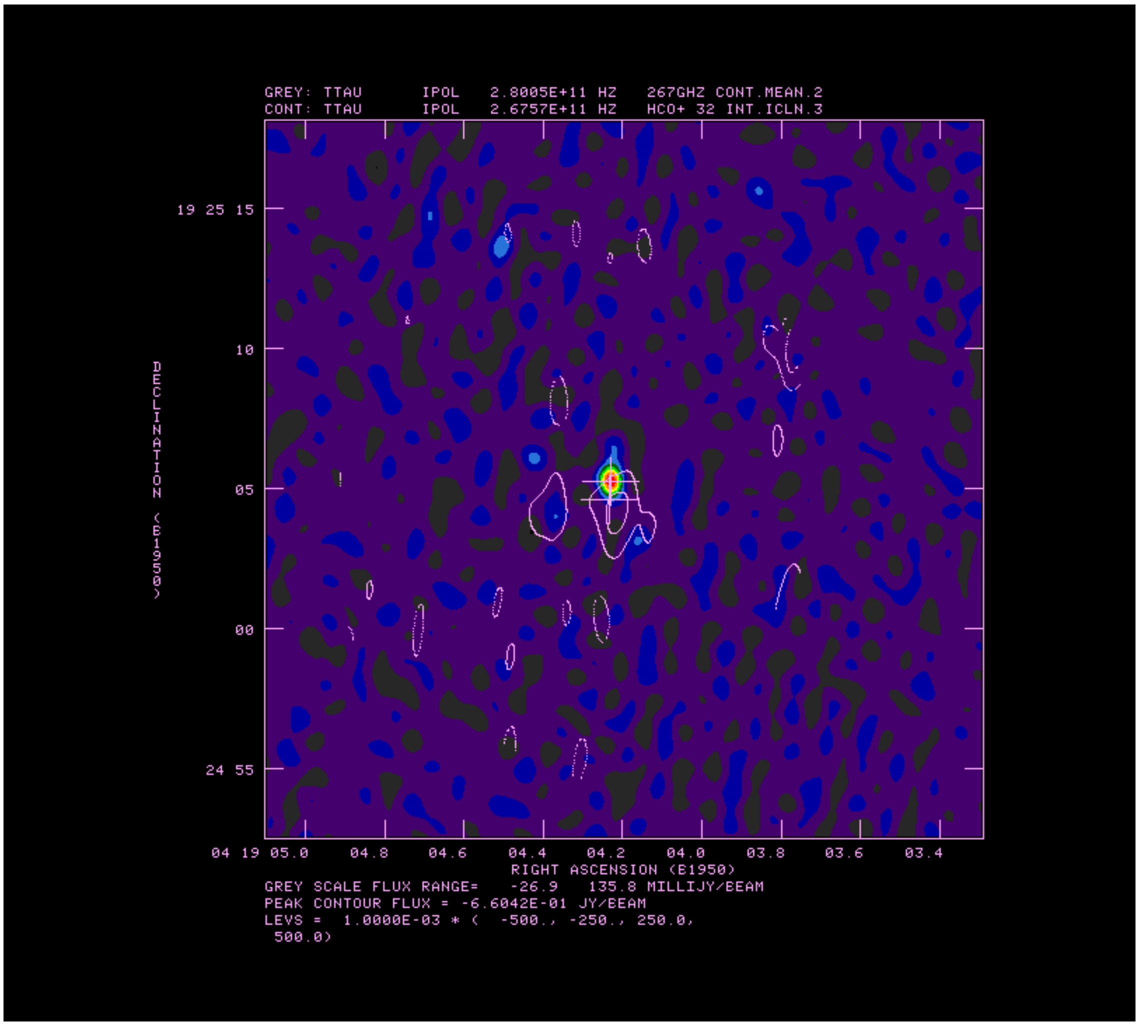

Fig. 1. *Continuum at 267 GHz and integrated* HCO^+ *J=3→2 (contours) at sub-arcsecond resolution. The positions of T Tau N and T Tau S are denoted by crosses.*

SPECTRAL ENERGY DISTRIBUTION

In Fig. 2 the spectral energy distribution of T Tau is given (many authors). A range of beam sizes has been used to measure the fluxes; different colors indicate different aperture ranges. Comparing the interferometer flux with previous single dish measurements we infer at least two components of *dust* emission: 1) circumbinary matter, tentatively in a flattened distribution that is resolved out with sub–arcsecond resolution and 2) a compact unresolved source associated with T Tau N. For a number of YSO's a similar two component for the dust emission has been invoked (Keene & Masson 1990, Terebey et al. 1993).

An empirical model has been constructed that shows the relative contributions of three components. Radio emission of T Tau N is modeled with a ν^α power law, with $\alpha = 0.8$. T Tau S is variable and has an uncertain power–law index (Skinner & Brown 1994). The emission is presumably non thermal and we have used $\alpha = 0.4$ in Fig. 2. For the dust around T Tau N we used a black body with $T_{\rm dust} = 40$ K and a dust opacity law with $\beta = 1.5$ The circumbinary matter has a temperature of 20 K. Using $\kappa_\nu = 0.1$ cm^2 g^{-1} (Hildebrand 1983), rough estimates for the disk masses are 0.02 $M_\odot$ for the T Tau N disk and 0.05 $M_\odot$ for the circumbinary material. For T Tau S the upper limit is 0.001 $M_\odot$.

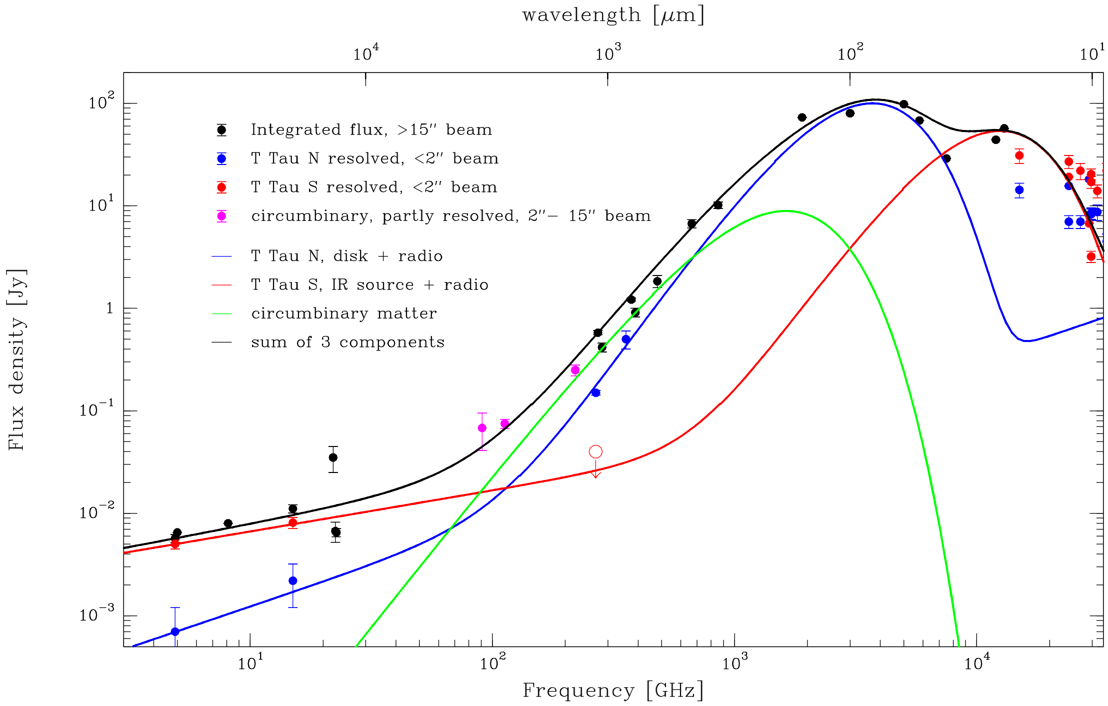

Fig. 2. *Spectral energy distribution for T Tau with different symbols for measurements with different apertures.*

THE CIRCUMBINARY GAS

We argued in Van Langevelde et al. (1994*a*) that the HCO^+ J=1→0 emission is absorbed by cold gas in the envelope, predominantly on the west side of T Tau. In this interpretation the HCO^+ J=3→2 is expected to be more symmetric around the binary, since less absorption is expected at this high transition. Unfortunately, most of the HCO^+ J=3→2 emission is resolved out by the interferometer, but some emission seems to originate close to the binary system. Using JCMT data, the size of the emitting region is $\approx 10''$. This leads us to identify this gas with the circumbinary material. The high excitation HCO^+ lines require warm and dense gas ($T \geq 70$ K and $n \geq 5 \cdot 10^5$ cm^{-3}) on large scales. The extended nature and narrow profile suggest that the emission is not related to the outflow.

From simultaneous ^{13}CO measurements it is known that the $C^{18}O$ J=1→0 emission is optically thin. It centers on the position of the continuum data (Fig. 3). The gas mass is estimated from the $C^{18}O$ to $< 0.01\ M_\odot$, assuming that the gas is homogeneously distributed in LTE at $T \leq 70$ K and $CO/H_2 = 8 \cdot 10^{-5}$ This gas mass can be compared with the combined estimate from dust around T Tau N plus the circumbinary material, although the $C^{18}O$ may become optically thick close to T Tau N. The CO seems to be depleted by at least a factor of 5, but a detailed density and temperature model is needed to confirm this.

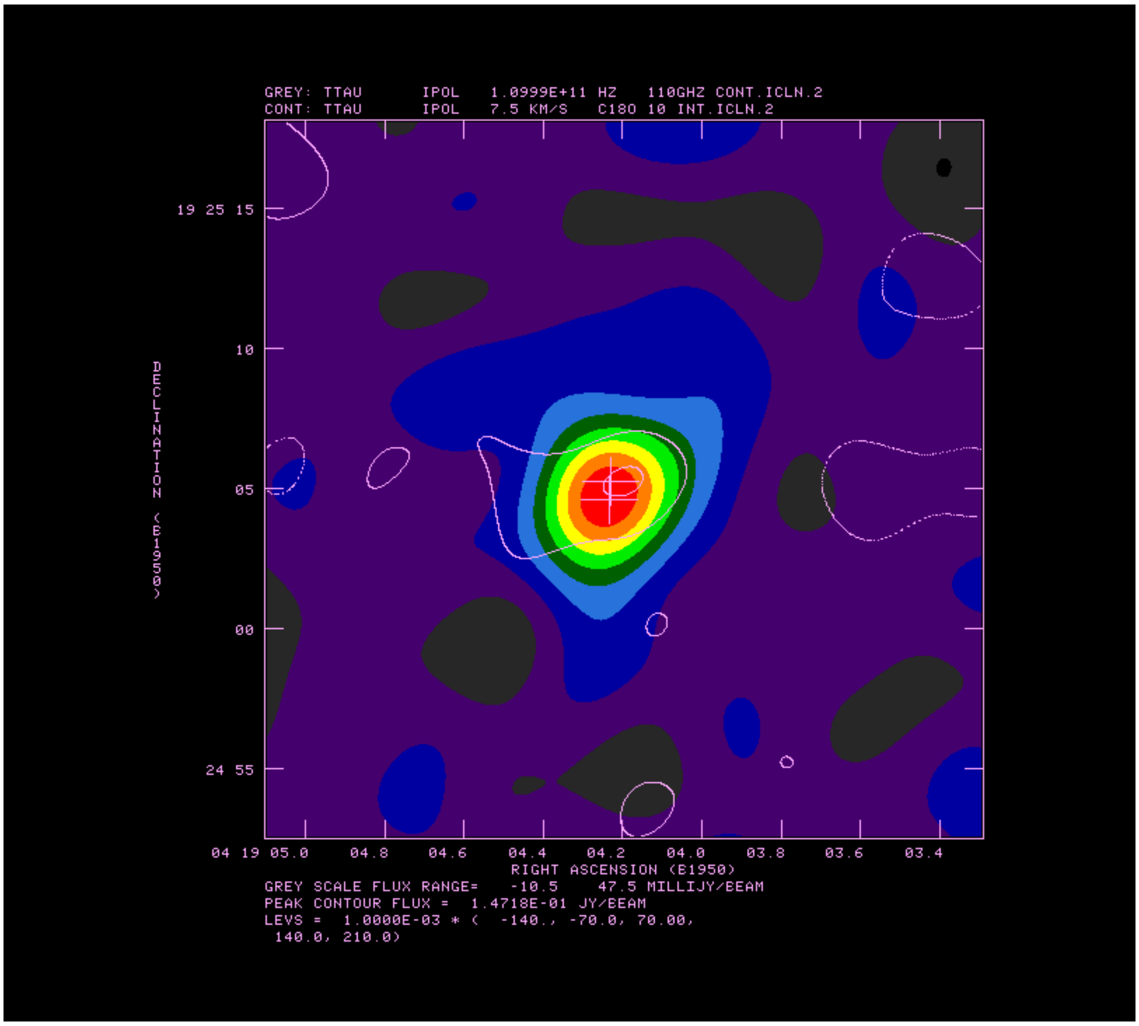

Fig. 3. *Continuum at 110 GHz (colors) and integrated* $C^{18}O$ *(contours). The positions of T Tau N and T Tau S are given by crosses.*

CONCLUSIONS

- Unresolved dust emission around T Tau N at sub–arcsecond resolution indicates the presence of a 70 AU, $\approx 0.02\ M_\odot$ circumstellar disk.
- For T Tau S an upper limit for a similar circumstellar disk can be derived $< 0.001\ M_\odot$.
- Considerable amounts of gas and dust seem to be present on a larger, circumbinary, scale of ≈ 1000 AU. An envelope mass of $\approx 0.05\ M_\odot$ is estimated.

- Preliminary estimates indicate a relatively low CO content in the circumbinary envelope, but a more detailed density and temperature model is needed to confirm this.

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