Aperture Synthesis Imaging of the Circumstellar Dust Disk Around DO Tauri

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ABSTRACT

We have detected the T Tauri star, DO Tauri, in a 0.6″-resolution VLA map of 43.3 GHz (λ = 7 mm) continuum emission. The 43 GHz flux density lies on the same power-law slope defined by 89 to 232 GHz measurements, $F_\nu \propto \nu^\alpha$ with index α = 2.39±0.23, confirming that the 43.3 GHz emission is thermal radiation from circumstellar dust. Upper limits to the flux densities at 8.4 and 22.5 GHz constrain the contribution of free-free emission from a compact ionized wind to less than 49%. The dust emissivity index, β, is 0.39±0.23, if the emission is optically thin. Fitting a model of a thin circumstellar disk to the observed spectral energy distribution gives $\beta = 0.6 \pm 0.3$, consistent with the power-law derivation. Both values are substantially lower than is generally accepted for the interstellar medium, suggesting grain growth. Given the youth of DO Tau and the early evolutionary state of its circumstellar disk, this result implies that mm-size grains have already formed by the early T-Tauri phase.

Subject headings: stars: individual: DO Tauri — stars: formation — circumstellar matter — planetary systems

1. Introduction

At least 50% of T Tauri stars (TTs) appear to be surrounded by circumstellar dust disks (Strom et al. 1989; Beckwith et al. 1990, hereafter BSCG; André & Montmerle 1994; Henning & Thamm 1994; Osterloh & Beckwith 1995). Global disk properties can be inferred from models of spectral energy distributions (SED's) from infrared to millimeter wavelengths (Adams, Lada, & Shu 1987; Beckwith & Sargent 1993; Mannings & Emerson 1994). Masses and sizes are similar to those assumed for the early solar nebula, suggesting that the disks may be protoplanetary (cf. BSCG; Beckwith & Sargent 1993). However, the SED models rely on assumptions about disk morphology and radial structure, and about the nature of the constituent dust grains.

Grain size and composition in these potentially planet-forming disks can be inferred from the spectral index, β, of the dust opacity (cf. Pollack et al. 1994) if thermal radiation from grains in the disk is optically thin. Sub-arcsecond resolution is necessary to image disks directly and measure properties on spatial scales of $\lesssim$100 AU at the distance of the nearest star-forming regions. At wavelengths longer than 3mm, the emission is well into the Rayleigh-Jeans part of the Planck curve and very likely to be optically thin. Dust continuum radiation has been detected from a number of TTs at λ = 3 mm (Sargent & Beckwith 1993 and references therein), but no thermal emission has been detected unambiguously at longer wavelengths (Mundy et al. 1993). The required spatial resolution and mJy sensitivities can now be achieved using the VLA at wavelengths of 7 mm.

DO Tauri is a young TTs in the Taurus star formation complex at a distance of 140 pc (Elias 1978; Kenyon, Dobrzycka, & Hartmann 1994). Estimates of its age and mass range from 1.6 to 6.0 $\times 10^5$ yrs and 0.3 to 0.7 $M_\odot$ (BSCG; Hartigan, Edwards & Ghandour 1995), depending on the theoretical tracks used to place it on the H-R diagram. The spectral energy distribution is consistent with the presence of a $\sim$0.01 $M_\odot$ circumstellar disk (BSCG; Beckwith & Sargent 1991, hereafter BS; Mannings & Emerson 1994). Asymmetric, blue-shifted, [OI] and [SII] forbidden line emission (Appenzeller, Jankovics & Östreicher 1984; Edwards et al. 1987; Edwards, Ray & Mundt 1993) is resolved as an optical jet at PA 70° (Hirth et al. 1994). The jet is approximately orthogonal to the direction of linear optical polarization, PA $\sim$ 170° (Bastien 1982), and to the long axis of CO (2$\rightarrow$1) emission detected in aperture synthesis images of DO Tau, PA $\sim$ 160° (Koerner & Sargent 1995). Kinematic models of the molecular line emission are consistent with the presence of a circumstellar disk that is centrifugally supported within a radius of 350 AU from DO Tau (Koerner 1994).

Here, we report on sub-arcsecond images of the λ = 7 mm emission from DO Tau which were made using the recently upgraded Very Large Array (VLA) of the National Radio Astronomy Observatory[1]. We have supplemented these measurements with continuum observations of DO

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Tau at other wavelengths to sample the spectral distribution of emission from $\lambda = 1.3$ mm to 3.6 cm and improve our understanding of grain properties in the circumstellar material.

2. Observations and Results

The VLA was used to observe DO Tau in radio continuum emission at 43.3, 22.5, and 8.4 GHz ($\lambda = 7$ mm, 1.3, and 3.6 cm). The phase center was offset $1''$ in both RA and Dec from the stellar position of DO Tau (Herbig & Bell 1988), and the total bandwidth was 100 MHz in right and left circular polarizations. As for all observations discussed below, molecular line emission is negligible within the narrow band. Observations at 43.3 GHz were carried out on 1994 April 3–4 with the inner seven antennas of the high-resolution A configuration, and on 1994 August 20 with 10 inner antennas of the B configuration. Baselines up to 5.6 km provided UV coverage in the range 30–800 kλ. On both dates, DO Tau was observed at 22.5 and 8.4 GHz using the remainder of the VLA's 27 antennas. UV coverage was 50–2700 kλ at 22.5 GHz and 20–1000kλ at 8.4 GHz. Absolute flux densities were calibrated using 3C48 and 3C286 with an estimated uncertainty of 20%. At 43.3 GHz, gain calibration was accomplished with periodic observations of 0333+321 with a measured flux density of 0.98 ± 0.06 Jy. At 22.5 GHz and 8.4 GHz, the gain calibrator was 0400+258 with flux densities 0.65 ± 0.03 Jy and 0.83 ± 0.01 Jy, respectively.

Data calibration and mapping used standard routines in the NRAO AIPS software package. Daytime atmospheric phase fluctuations during A array observations necessitated extensive editing and application of a Gaussian taper to the UV data, resulting in a $0.68'' \times 0.53''$ (FWHM) synthesized beam at PA -78°. This corresponds to $95{\times}74$ AU at DO Tau. Fig. 1a displays the CLEANed image of DO Tau at 43.3 GHz. An unresolved source with flux density 1.80 $\pm$0.71 mJy is detected at the stellar position, $\alpha(1950) = 04^h35^m24.19^s$, $\delta(1950) = 26^\circ04'54.5''$. The $\pm$0.71 mJy uncertainty includes rms variations in the map ($\pm$ 0.35 mJy bm^{-1}) and a possible 20% error in absolute flux calibration. At 22.5 and 8.6 GHz, DO Tau was not detected within the area encompassed by the 43.3 GHz synthesized beam to 3σ levels of 0.76 and 0.17 mJy, respectively.

Observations were made with the Owens Valley millimeter array at 89.2, 111.2, 221.5, and 232.0 GHz (corresponding to $\lambda = 3.4$, 2.7, 1.4, and 1.3 mm) between 1993 September and 1995 March. Measurements at 89 GHz were made with six telescopes; four were used at 110 GHz, and five at 220 and 230 GHz. Overall UV-ranges were 5–60 kλ (89 GHz), 5–25 kλ (110 GHz), and 10–55 kλ (220 Hz and 230 GHz). Resulting FWHM synthesized beams are listed in Table I. Antenna gains were determined from periodic observations of 0528+134 and absolute flux density calibration was based on measurements of Uranus. Data were calibrated using the Owens Valley software package, MMA, and mapped with AIPS. At all four frequencies, continuum emission is unresolved and peaks at the position of the VLA 43.3 GHz image. Aperture synthesis maps at 89

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and 220 GHz are displayed in Fig. 1b and 1c. Measured flux densities at all frequencies are listed in Table I and displayed in Fig. 2.

3. Modeling and Discussion

Our measurements of DO Tau between 8.4 and 230 GHz can be fit by a single power law, $F_\nu \propto \nu^\alpha$, with index $\alpha = 2.39 \pm 0.23$, shown as a solid line in Fig. 2. Earlier detections of radio emission from TTs at wavelengths greater than 1.3 cm yielded values of α between 0 and 1 (Bieging, Cohen & Schwartz 1984) and have been attributed to free-free emission from ionized outflows (Reynolds 1986). Extrapolating from the upper limit of 8.4 GHz emission with $\alpha = 1$ (dotted line in figure 2), we estimate that no more than 49% of DO Tau's 43.3 GHz emission can arise as free-free radiation from an ionized jet. Fig. 2 suggests the observed mm-wave flux originates entirely from circumstellar dust.

The frequency dependence of the mm-wave dust opacity, β, can be derived from α, since $\alpha \approx 2 + \beta/(1+\Delta)$, where Δ is the ratio of optically thick to optically thin emission from the disk (BS, eqn. 1). At frequencies where emission from a circumstellar disk is largely optically thin and the Rayleigh-Jeans approximation holds, $\beta \approx \alpha - 2$. For DO Tau, continuum emission appears to be largely optically thin, even at sub-millimeter wavelengths (BS; Mannings & Emerson 1994). We estimate 0.39 ± 0.23 for β_{1-7mm}, in good agreement with the BS value of $\beta_{0.6-1mm}$, 0.4 ± 0.2. There is no evidence for the change in β longward of 2mm, postulated by Mundy et al. (1993) for a few other TTs.

An estimate of β can also be obtained by fitting the spectral distribution of luminosity $L_\nu = 4\pi D^2 \nu F_\nu$ with a disk model which takes into account any contribution from optically thick emission. Following BSCG and Adams et al. (1990), we assumed power-law radial profiles in disk temperature and surface density, $T = T_0(R/R_0)^{-q}$ and $\Sigma = \Sigma_0(R/R_0)^{-p}$ with p = 1.5 or 1.75. The millimeter-wave emissivity of the grains, κ, is $0.1(\nu/10^{12}Hz)^\beta$ cm^2 g^{-1}. The outer radius, R_d, was allowed to take on values between 22 and 350 AU; the former is the lower limit to disk size if all 1 mm emission is optically thick (BS); the latter is the deconvolved half-maximum radius of the CO-emitting region from aperture synthesis images. These suggest a disk inclination angle, θ, of 40° (Koerner & Sargent 1995). From the 12, 25, and 60 μm IRAS fluxes, which probe optically thick regions of the disk, we obtain T = 218 K at 1 AU with q = 0.54, very close to the value derived by BSCG for a face-on disk. Best-fit values of β and M_d, the total disk mass, were estimated from the minimum reduced χ^2 value. Acceptable fits, with χ^2 falling within $\Delta\chi^2 = 1$ of its minimum value, were found for our entire range of p and R_d values. The best-fit model, with $\beta = 0.6 \pm 0.3$, $M_d = 1.0 \pm 0.5 \times 10^{-2}\ M_\odot$, p = 1.75, R_d = 350 AU, and $\chi^2 = 0.77$, is plotted in Fig. 3 as a solid line, along with the luminosity distribution derived from IRAS, sub-millimeter, and millimeter observations of DO Tau. Following BSCG (eqn. 20), these parameters yield $\Delta \approx 0.28$ at λ = 3 mm and make possible a revised estimate of β from the power-law fit to data presented here. For $\Delta = 0.28$ and $\alpha = 2.39$, we obtain $\beta = 0.50 \pm 0.23$, in good agreement with the value obtained from both our disk-model fit and that of Mannings & Emerson (1994).

For the ISM, it is commonly assumed that β is about 2 in the millimeter wavelength regime (Mathis 1990). However, a value of 1.3 has been obtained in recent laboratory studies (Agladze et al. 1994). Even lower values are suggested by sub-millimeter observations of T Tauri disks (BS; Mannings & Emerson 1994). A variety of explanations have been proposed, including chemical composition, physical shape, and grain growth (Wright 1987; BS; Krügel & Siebenmorgen 1994; Ossenkopf & Henning 1994; Pollack et al. 1994).

For DO Tau, we find $\beta \approx 0.5$ and contend that our denser sampling of the sub-millimeter regime and spectral coverage extending to longer wavelengths effectively eliminates uncertainties that may have complicated other derivations. Grain properties in circumstellar disks are unlikely to display the exotic range of chemical composition and physical shapes required to reproduce this result in the laboratory. By contrast, the growth of grain size distributions to include particles larger than 1 mm accounts for our value of β (cf. Miyake and Nakagawa 1993) and is consistent with the short theoretical timescales ($\sim$ 100 yr) for production of mm-size particles in the early solar nebula (cf. Fig. 19, Cuzzi, Dobrovolskis, & Champney 1993).

If the average grain size in disks steadily increases due to planetesimal formation, β should decrease monotonically with age. However, DO Tau is relatively young, only a few $\times\ 10^5$ yrs, with an outflow typical of an active disk. Grain growth appears to have already occurred by the early T-Tauri phase. Recent 7 mm images of a very young protostar, HH24MMS (Chandler et al. 1995), also yield a lower value of β than found for many older TTs in sub-millimeter surveys (cf. BS). These results are inconsistent with a simple picture of gradually decreasing β; they could be explained if mm-size grains grow quickly, followed by generation of a new population of small dust grains by planetesimal collisions (Lissauer & Stewart 1993). Long-wavelength observations of a statistical sample of TTs disks encompassing a range of ages are clearly required to test this hypothesis.

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Frequency (GHz)	Flux Density (mJy)	Statistical error (mJy)	Total error (mJy)	Synthesized B_{maj}	Beam B_{min}	Parameters PA
8.4	<0.17 (3σ)	...	...	0.41″	0.38″	120°
22.5	<0.76 (3σ)	...	...	0.25″	0.23″	−10°
43.3	1.80	0.35	0.71	0.68″	0.53″	−78°
89.2	14.2	0.9	3.74	2.86″	2.10″	82°
111.2	30.2	4.5	10.5	13.0″	5.4″	−69°
221.5	98.6	4.9	24.2	3.98″	3.15″	62°
232.0	137.5	4.9	32.4	3.41″	3.15″	−84°

Table 1: Radio (VLA) and mm-wave (OVRO) Continuum Flux Densities from DO Tauri. Total errors include 20% uncertainty in the absolute flux density calibration.

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