

# Large grains in the disk of CQ Tau

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**Abstract.** We present 7 mm observations of the dusty disk surrounding the 10 Myr old  $1.5 M_{\odot}$  pre-main-sequence star CQ Tauri obtained at the Very Large Array with 0.8 arcsec resolution and 0.1 mJy rms sensitivity. These observations resolve the 7 mm emission in approximately the north-south direction, confirming previous results obtained with lower resolution. We use a two-layer flared disk model to interpret the observed fluxes from 7 mm to 1.3 mm together with the resolved 7 mm structure. We find that the disk radius is constrained to the range 100 to 300 AU, depending on the steepness of the disk surface density distribution. The power law index of the dust opacity coefficient,  $\beta$ , is constrained to be 0.5 to 0.7. Since the models indicate that the disk is optically thin at millimeter wavelengths for radii greater than 8 AU, the contribution of an optically thick region to the emission is less than 10%. This implies that high optical depth or complex disk geometry cannot be the cause of the observed shallow millimeter spectral index. Instead, the new analysis supports the earlier suggestion that dust particles in the disk have grown to sizes as large as a few centimeters. The dust in the CQ Tauri system appears to be evolved much like that in the TW Hydra system, a well-studied pre-main-sequence star of similar age and lower mass. The survival of gas-rich disks with incomplete grain evolution at such old ages deserves further investigations.

**Key words.** stars: planetary systems: protoplanetary disks – stars: planetary systems: formation – stars: formation – stars: individual: CQ Tauri

## 1. Introduction

Grain growth from the sub-micron size, typical of dust in the ISM, to millimeter and centimeter sizes is the first step toward the formation of planets inside circumstellar disks. We expect that such growth either occurs during the pre-main-sequence (PMS) life of the star, when the circumstellar disks are still gas-rich, or that it will never take place (Ruden 1999).

So far, there is little firm observational evidence for very large grains in the disks of PMS stars (Beckwith et al. 2000). The best indication comes from the shallow wavelength dependence of the millimeter emission from dust in most PMS disks (e.g. Beckwith & Sargent 1991). Namely, if the emission is optically thin, the measured spectral index  $\alpha$  ( $F_{\nu} \propto \nu^{\alpha}$ ) is directly related to the dependence of the opacity on wavelength. The grain size can then be inferred from the opacity law, as long as optical depth and geometrical effects can be sorted out. This requires that the spectral energy distribution (SED) is well known and that the disk is spatially resolved at one or more wavelengths in the millimeter range (see e.g. the discussion in Testi et al. 2001).

Recently, this method has been applied to the nearby T Tauri star (TTS) TW Hya by Calvet et al. (2002), who have analyzed the SED of TW Hya together with a 7 mm VLA map

obtained by Wilner et al. (2000). Using self-consistent disk models, they showed that the observations could only be reproduced if the grains in the outer disk have grown to centimeter sizes.

We report in this paper similar results on the PMS star CQ Tau. CQ Tau is a well studied variable star of spectral type  $\sim A8$ , mass  $1.5 M_{\odot}$ , age  $\geq 10$  Myr. With a distance of about 100 pc (Hipparcos), it is one of the closest young intermediate mass stars still surrounded by a massive circumstellar disk (Natta et al. 2000). Its SED has been modelled as due to a circumstellar disk by various authors (Chiang et al. 2001; Natta et al. 2001). At millimeter wavelengths, it has been observed with the OVRO interferometer (Mannings & Sargent 1997, 2000), with Plateau de Bure (Dutrey et al., private communication; quoted by Natta et al. 2001) and with the VLA at 7 mm and 3.6 cm (Testi et al. 2001). The millimeter SED is characterized by a spectral index  $\alpha_{\text{mm}} \sim 2.4\text{--}2.6$ , which suggests the presence of grains much larger than in the ISM. However, as discussed by Testi et al. (2001), given the available data, two classes of models can explain the observed fluxes and spectral index: small optically thick disks with standard ISM dust, or bigger, optically thin disks with large grains. As the disk was possibly resolved in our VLA D-array observations, the large grains hypothesis was favoured. However, to solve the ambiguity between grains and disk properties it is necessary to

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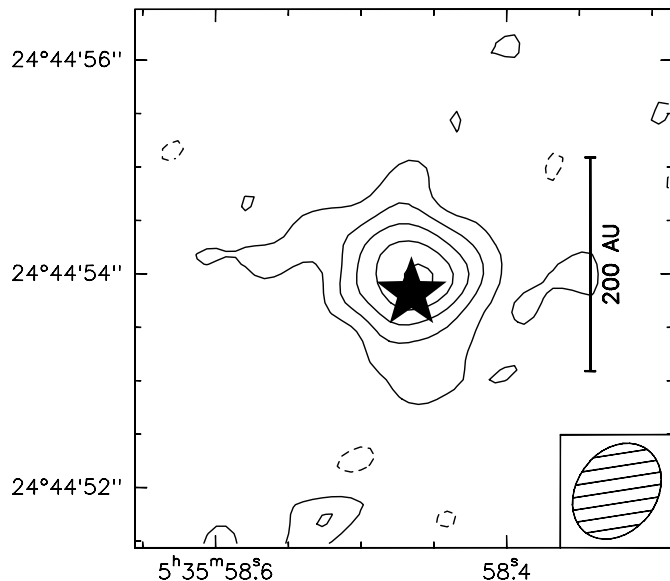
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clearly resolve the disk and to derive disk structural parameters (mainly the outer radius and surface density distribution). We have thus obtained new VLA 7 mm observations from a more extended VLA configuration to better resolve the disk, and we model these new data together with previous millimeter-wave observations.

## 2. VLA 7 mm observations and results

CQ Tauri was observed at  $Q$ -band (7 mm, 43 GHz) with the NRAO<sup>1</sup> VLA on July 21 and 31, 2001. The array was in the C configuration, and the 24 antennas equipped with  $Q$ -band receivers offered baselines in the range from 35 m to 3.4 km. 3C286 was used as primary flux calibrator, while 0547+273, whose flux was measured to be 0.52 Jy at 7 mm, was used as phase and amplitude calibrator. Hourly pointing at X-band (3.6 cm, 8.4 GHz) was used to ensure accurate pointing during the observing run. The raw visibility data was edited and calibrated within the AIPS software package using standard techniques. The calibrated C-array ( $u, v$ ) dataset was merged with the calibrated D-array data from Testi et al. (2001) and then exported to the MIRIAD package for deconvolution and modeling. All maps presented in this paper have been obtained with natural weighting of the visibilities; the resulting synthesised beam  $FWHM$  is  $0''.97 \times 0''.75$  with position angle  $-36^\circ$ , the noise level in the map is 0.1 mJy/beam.

The combined C- and D-array 7 mm map of CQ Tau is shown in Fig. 1. The new data confirm and extend the findings of Testi et al. (2001). The millimeter peak is coincident with the position of the optical star as measured from Hipparchos. The 7 mm emission from the CQ Tau system is resolved and elongated approximately in the north-south direction. The  $2\sigma$  contour has a maximum elongation slightly exceeding  $2''$  (200 AU). The east-west “plume” at  $\alpha \sim 5:35:58.55$ ,  $\delta \sim 24:44:54$  is not significant in our data and will be treated as a noise peak in this paper; nevertheless it would be interesting to check in the future with additional observations whether this is a real feature or not. Results from a two dimensional Gaussian fit to the continuum image are consistent with our previous D-array results, albeit yielding a marginally smaller source size: the deconvolved  $FWHM$  is  $190 \times 70$  AU. Assuming a circularly symmetric source, the observed aspect ratio implies an inclination of the disk axis from the line of sight of  $\sim 70^\circ$ , consistent within uncertainties with both our D-array estimate and the  $66^\circ$  inclination derived from an analysis of the optical photometric and polarimetric variability by Natta & Whitney (2000). The fact that with the new higher angular resolution C-array data we derive deconvolved disk sizes smaller than those previously determined with D-array data is not surprising. Due to the centrally peaked nature of the disk emission, interferometric continuum maps will always emphasize the central regions of the disk and may lose the outer regions due to insufficient surface brightness



**Fig. 1.** VLA C+D array 7 mm map of CQ Tau. Contour levels start at  $2\sigma$  and are spaced by  $2\sigma$  (both negative and positive),  $1\sigma = 0.1$  mJy/beam. The synthesised beam  $FWHM$  ( $0''.97 \times 0''.75$  at  $PA = -36^\circ$ ) is shown by the shaded ellipse in the inset. The vertical bar shows the angular extent of 200 AU at the distance of CQ Tau (100 pc). Based on Hipparchos position and proper motion measurements, the star marks the position of the optical star at the epoch 2001.0, intermediate between the two VLA epochs. The maximum proper motion shift between the two epochs is expected to be  $\sim 28$  mas in the north-south direction.

sensitivity or due to spatial filtering of the largest scales (see also the discussion in Dutrey et al. 1996; Wilner et al. 2000).

In order to correctly derive the disk parameters, the observed interferometric maps should be compared with models of the disk emission sampled on the same ( $u, v$ ) points and deconvolved in the same manner as the observations. This analysis will be presented in the following section.

## 3. Models

We compare our observations to the predictions of disk models based on the two-layer approximation first described by Chiang & Goldreich (1997; CG97). The disk consists of a surface layer which intercepts the stellar radiation and re-emits 1/2 of it toward the observer and 1/2 toward the disk midplane. The midplane is in turn heated by the radiation reprocessed by the surface layer, and it is therefore cooler than grains on the surface. These models solve the radiation transfer in a simple way, and allow a self-consistent computation of the geometry of the disk, assuming hydrostatic equilibrium in the vertical direction.

Our models are an improved version of the original CG97 models. We have implemented a more accurate iterative scheme to compute the disk flaring angle at each radius (Chiang et al. 2001) and a more realistic dust model for the surface grains. In addition, we take advantage of the capability of the two-layer scheme to use two different dust prescription for the midplane and surface. Details can be found in Natta et al. (2001) and Dullemond et al. (2001).

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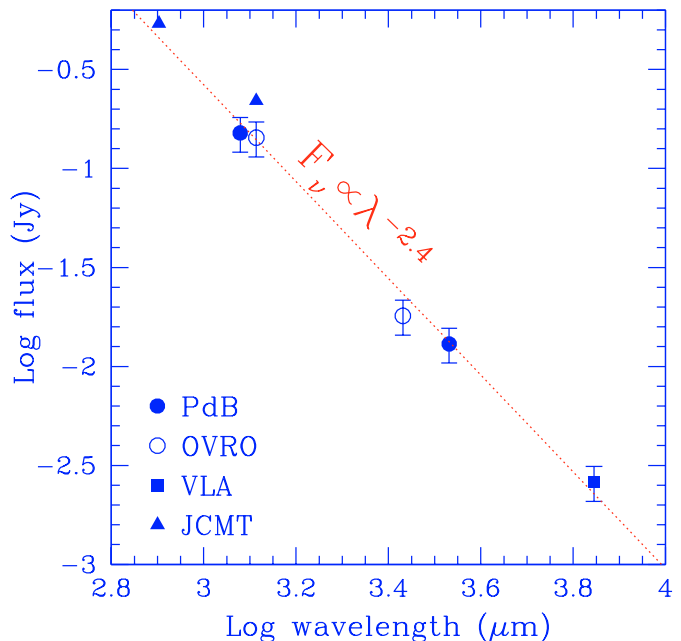
At mm wavelengths, the predictions of these two-layer models are rather robust, both in terms of integrated flux and of intensity profiles. For example, there is no significant difference between the results from our models and those from models where the radiation transfer is properly solved in the vertical direction (Dullemond et al. 2002; Dullemond & Natta 2003a). Furthermore, the use of a mean opacity for the grains in the disk midplane does not affect the results in any relevant way (see Wolf 2003 and references therein), and the effect of scattering of the stellar radiation by grains in the disk (which is not included in the models) is also negligible (Dullemond & Natta 2003b).

To compute a model, we need to specify the stellar properties (luminosity  $L_*$ , effective temperature  $T_{\text{eff}}$ , mass  $M_*$  and distance  $D$ ) and some disk parameters, namely the inner and outer radius ( $R_{\text{in}}$  and  $R_{\text{d}}$ , respectively) and the surface density distribution  $\Sigma = \Sigma_0(R/R_0)^{-p}$ , where  $R_0$  is a fiducial radius. The disk mass  $M_{\text{d}}$  is then fixed. The other parameters needed are the dust properties on the surface and in the midplane. We describe the midplane dust opacity as a power-law function of  $\lambda$ ,  $\kappa = \kappa_0(\lambda/\lambda_0)^{-\beta}$ , with  $\lambda_0 = 1.3$  mm and  $\kappa_0 = 1.0$  cm<sup>2</sup> g<sup>-1</sup> of dust (Hildebrand 1983). For grains on the surface, we use a MRN mixture of graphite and silicates with 10% of cosmic carbon in grains of radius between 0.02 and 0.35  $\mu\text{m}$  and 100% cosmic silicon in silicates of radius between 0.02 and 0.7  $\mu\text{m}$  (see Natta et al. 2001). This choice is not important for the disk properties at millimeter wavelengths, as long as the disk is optically thick to the stellar radiation.

We assume that the stellar properties are known ( $L_* = 4 L_{\odot}$ ,  $T_{\text{eff}} = 6900$  K). The exact value of the disk inner radius is not important, and we fix it at  $R_{\text{in}} = 10 R_*$ , i.e., close to the dust sublimation radius. We then vary  $\Sigma_0$ ,  $p$ ,  $R_{\text{d}}$  and  $\beta$  and compute the disk SED (integrated over the disk surface) for a distance  $D = 100$  pc and an inclination of  $66^\circ$ .

We first select the models that reproduce the *integrated* observed fluxes at 1.3, 3 and 7 mm (see Fig. 2) within the observational uncertainties, keeping in mind the 3.6 cm results of Testi et al. (2001), who constrain any possible contamination from free-free emission at millimeter wavelength to be negligible. For the accepted models we then compute 7 mm synthetic maps and compare them to the observed one. To this purpose we followed the method outlined by Wilner et al. (2000): each model image is Fourier-transformed and sampled on the same  $(u, v)$  points as the 7 mm C- and D-array VLA datasets; the resulting visibilities are then treated in the same way as the observational data in order to produce synthetic maps to be compared with the observed ones. The position angle of the disk is not well constrained by the Gaussian fits of the observed emission. We computed a set of models with different position angles on the sky, the best results are obtained for position angles in the range  $20^\circ$  to  $30^\circ$ , depending on the other disk parameters.

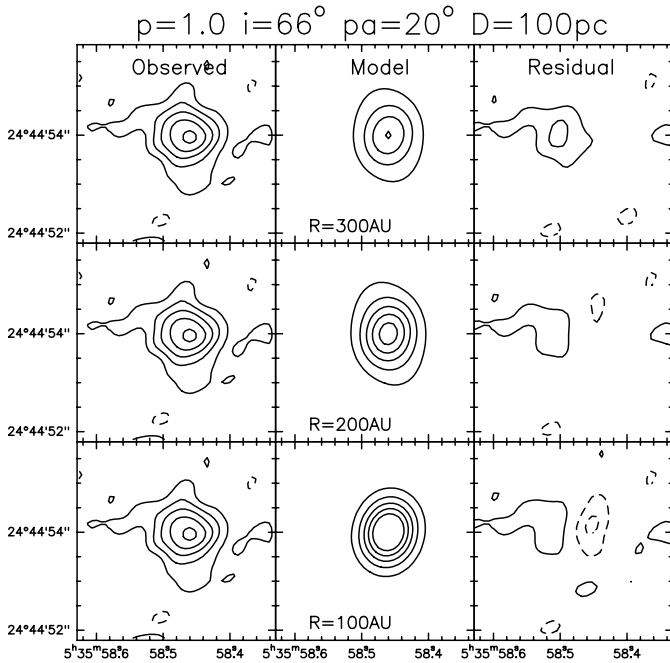
We compare the observed and model maps by showing the residual image obtained by subtracting the noise-free model from the observed image. The results for  $p = 1.0$  are shown in Fig. 3. Since the disks are optically thin at most radii, (except the very inner regions with  $R < 8$  AU) and they have to reproduce the total integrated flux, very large disks ( $R \geq 300$  AU) predict an observed surface brightness that is too low



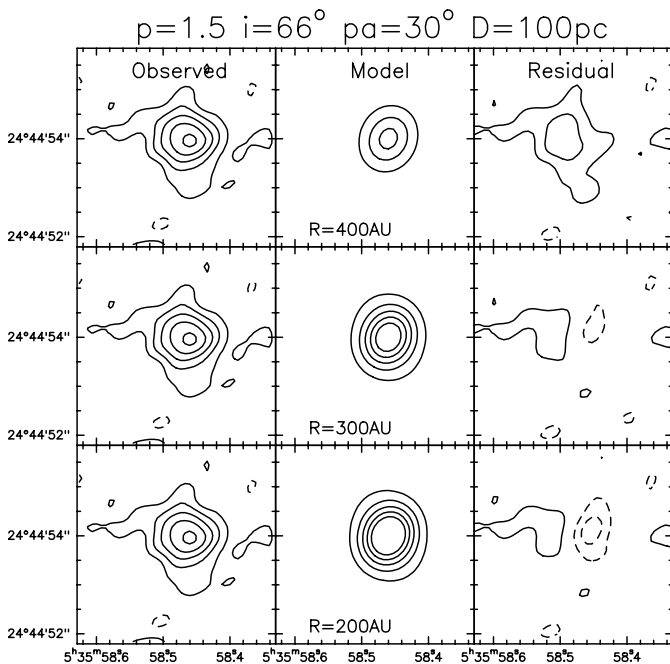
**Fig. 2.** Observed fluxes of CQ Tau. OVRO points are from Mannings & Sargent (1997); PdB from Dutrey, quoted by Natta et al. (2001); JCMT from Mannings, quoted by Natta et al. (2001); the VLA 7 mm point is from Testi et al. (2001). Note that we have plotted for all interferometric points a calibration uncertainty of  $\pm 20\%$ , even when the formal errors are smaller. The best fitting slope  $-2.4$  has been derived from the interferometric data only.

compared with observations, while small disks ( $R \leq 100$  AU) are too compact and have a much higher surface brightness than observed. The best match between observations and model is found for  $R \sim 200$  AU. We also investigate the possibility of shallower or steeper surface density gradients. Steep surface density gradients ( $p = 1.5$ , Fig. 4) require larger disk radii to reproduce the observed images, the best match in this case is for  $R \sim 300$  AU. Shallow surface density gradients have been recently claimed for many TTS disks (Kitamura et al. 2002); the comparison of our CQ Tau map with models with  $p = 0.5$  is shown in Fig. 5. The best match, in this case, is for  $R \sim 100$  AU, the residuals are marginally larger than in the  $p = 1.0$  and  $1.5$  best models, but the difference is not really significant. The dependence of the outer radius on the surface density law is not unexpected, see also the discussion of Mundy et al. (1996). In all cases the outer radius is slightly or significantly larger than the *FWHM* radius derived from the 2D Gaussian deconvolution of the 7 mm map; especially if  $p \geq 1$ , our observations are consistent with CQ Tau having a rather large disk, comparable in size to the CO disks observed around other Herbig Ae stars (Mannings & Sargent 1997, 2000).

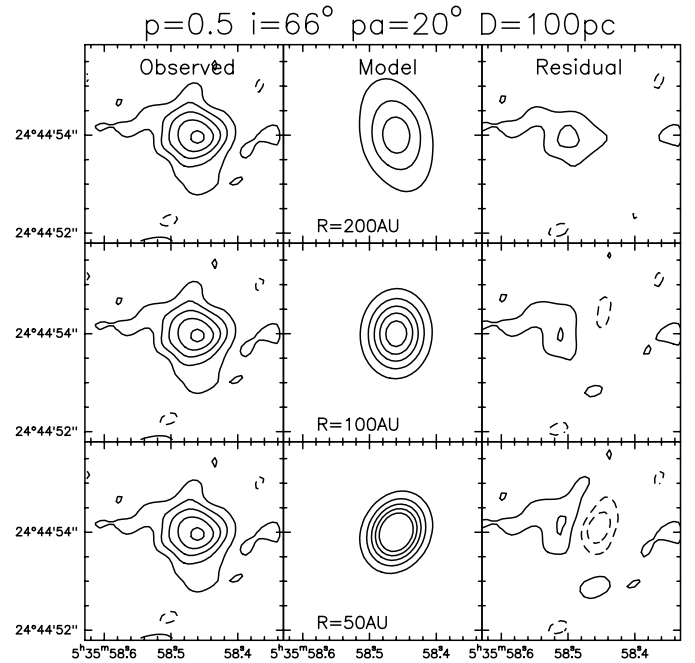
The values of the exponent  $\beta$  for the best matching models range from 0.55 for disks with flat density profile ( $p = 0.5$ ) to 0.6 for  $p = 1$  and 0.7 for  $p = 1.5$ . In all these models, at 1.3 mm the contribution of the inner optically thick disk ( $\sim 8$  AU at most) to the total flux is  $< 10\%$ . Thus our modeling of the observed 7 mm VLA map, together with the constraint on the integrated fluxes from 1.3 to 7 mm, confirm that the millimeter emission of CQ Tau originates from an optically



**Fig. 3.** Comparison between observed and synthetic 7 mm images of the CQ Tau protoplanetary disk. The observed image is shown in the left panels, with the same contour levels as in Fig. 1: contours start at  $2\sigma$  (positive and negative) and are spaced by  $2\sigma$ . The synthetic models images are shown in the central panels for different values of the disk radius, the surface density power-law index ( $p$ ), the inclination ( $i$ ) and position (PA) angles are the same for all the models shown in this figure:  $p = 1.0$ ,  $i = 66^\circ$ ,  $PA = 20^\circ$ . The disk radii are  $R = 100$ , 200, and 300 AU as labelled. On the right panels we show the residuals after subtracting the model images from the observed image. Contour levels are the same in all panels. *All the models shown here reproduce the observed integrated fluxes at 1.3, 3 and 7 mm.*



**Fig. 4.** Same as Fig. 3 but for  $p = 1.5$ ,  $PA = 30^\circ$ , and  $R = 200$ , 300, and 400 AU.



**Fig. 5.** Same as Fig. 3 but for  $p = 0.5$  and  $R = 50$ , 100, and 200 AU, respectively.

thin disk with grains very different from those in the ISM. No model with a significant contribution from an optically thick inner disk fits the data, even if we relax the condition that the CQ Tau disk is highly inclined. We could not find any model with ISM dust in the disk midplane that would reproduce the observations. On the other extreme, there is no possible fit if the opacity is wavelength-independent ( $\beta \sim 0.0$ ), as it would be for extremely large grains (“pebbles”).

The disk mass of the best matching models does not depend strongly on  $p$  or  $R_d$  (due to the negligible contribution from the optically thick region). Assuming a gas-to-dust mass ratio of 100, calculated disk masses are of the order of  $0.1 M_\star (0.012, 0.016 \text{ and } 0.017 M_\odot \text{ for } p = 0.5, 1.0, \text{ and } 1.5, \text{ respectively})$ . Note, however, that the models do not constrain the actual disk mass, but rather the product  $M_{\text{dust}} \times \kappa_0$ , and the values just quoted correspond to a  $\kappa_0 = 1 \text{ cm}^2 \text{ g}^{-1}$  for dust particles, independently of  $\beta$  (see Sect. 4).

#### 4. Discussion

If we are observing thermal, optically thin emission from dust particles, then the derived opacity law is quite robust. Not only is it independent of the disk geometry, but also of the temperature values and/or gradient, as long as  $T \gg hv/k$ . This is always the case in all the models we have considered. Similarly, density irregularities in the disk will have no effect on the measured  $\beta$ . The models of the previous section assume that the disk is flared and that dust and gas are well mixed together. This is likely to be the case, since both the shape of the SED at shorter wavelengths (Chiang et al. 2001; Natta et al. 2001) and the characteristic polarimetric variability of CQ Tau (Natta & Whitney 2000) are well fitted by flared disks. Our millimeter observations agree with this result, but are also consistent

with geometrically flat disks. In fact, because of the optically thin emission, the millimeter images are probing the bulk of the dust material which is located on the mid-plane in flared disks. Nevertheless, it is important to note that flat disks models are not self-consistent and require an “ad hoc” choice of the dust temperature profile. In this context it is also important to note that the 3.6 cm upper limit measured by Testi et al. (2001) imply that any possible contamination of the millimeter flux from free-free emission must be very low ( $\ll 10\%$  at 7 mm), and its possible impact on the derived dust opacity law is negligible.

Our observations exclude the possibility that the CQ Tau disk is very small ( $\leq 30$  AU), optically thick and composed of ISM grains (see the discussion in Testi et al. 2001). If this were the case, the 7 mm emission would not be resolved and the match between the observed and expected disk maps would be much worst than the lower panels of Figs. 3, 4, and 5.

We reiterate here that the grains we are discussing are those located in the outer ( $R \geq 5\text{--}10$  AU) disk midplane, which contains most of the mass. We expect that grains on the disk surface will be different, very likely much smaller. Those “surface” grains determine the SED at shorter wavelengths, as discussed, for example, by CG97. Chiang et al. (2001) obtain a rather good fit to the CQ Tau SED with a face-on disk model where the surface dust is a MRN distribution of iron and amorphous olivine with minimum and maximum radii of 0.01 and 1  $\mu\text{m}$ , respectively. When the temperature drops below 150 K, the silicate grains are coated with thick mantles of water ice, whose features at 45 and 62  $\mu\text{m}$  contribute to enhance the far-infrared flux. The midplane dust has a maximum size of 1 mm, size distribution  $n(a) \propto a^{-3.5}$ ;  $\Sigma$  is  $\propto R^{-1.5}$ , the disk model has a mass of 0.04  $M_{\odot}$  and outer radius 180 AU. These disk parameters are not very different from what we derive. However, a maximum grain size of 1 mm will result in an opacity which drops too steeply at 7 mm to account for our observations. Natta et al. (2001) fit the same SED (which extended only to 2.6 mm) with a small ( $R_d = 50$  AU), very tilted ( $\theta = 66$  deg) disk, same surface density profile,  $M_d = 0.02 M_{\odot}$  a mixture of silicates and graphite for the surface dust similar to what adopted here, and midplane dust opacity  $\kappa \propto \lambda^{-1}$ . Also this set of parameters would fail to reproduce the characteristics of our 7 mm emission. As noticed in Sect. 3, the disk emission at millimeter wavelengths is determined by the midplane grain and disk properties, and it is not affected by the nature of the surface dust. Consequently, in this paper, we have not made any effort to select the best parameters for the surface dust to fit the near and far-infrared CQ Tau SED.

The Chiang et al. (2001) and Natta et al. (2001) results show that disk models, that allow for different dust properties on the disk surface and midplane, can account for the CQ Tau SED at all wavelengths. This is important, because a serious concern in our analysis is the possibility that CQ Tau retains a residual envelope of dust which enshrouds the disk and dominates its millimeter emission. The effects of such an envelope on the disk temperature and on the overall observed SED have been discussed by Natta (1993) and more recently, among others, by Kikuchi et al. (2002). Although no model specific for CQ Tau has been computed, envelopes with shallow density profiles (shallower than  $r^{-1}$ ) produce mid and far-infrared

excess emission in the SED, not very different from what is observed in CQ Tau (Natta et al. 2001). However, as we have seen, also two-layer disk models can account for it. Additionally, the contribution of envelopes to the small-scale millimeter flux detected with the interferometers is generally negligible (see, for example, Butner et al. 1994). This is very likely the case of CQ Tau, given that the JCMT flux at 1.3 mm, obtained with a beam of about 20 arcsec, is only  $\sim 50\%$  larger than the flux measured by the interferometers, and that this difference is in fact comparable with the calibration uncertainties of both measurements.

Let us, therefore, consider the implications of our result, namely that the mean opacity of the grains in the CQ Tau outer disk midplane has a wavelength dependence  $\kappa \propto \lambda^{-0.6 \pm 0.1}$  in the millimeter. It is customary to interpret small values of  $\beta$  as evidence of grain growth. Miyake & Nakagawa (1993) have shown that the mass opacity coefficient of a distribution of silicates and ice with  $n(a) \propto a^{-3.5}$  has  $\beta \lesssim 1$  in the millimeter if the maximum grain radius increases to values of 0.1–10 cm, depending on the porosity of the grains. Recently, D’Alessio et al. (2001) have explored the effect of grain growth on disk properties using the dust model of Pollack et al. (1994). They find that  $\beta \sim 0.6$  is reproduced for  $T < 100$  K, i.e., when ices are present, by a size distribution  $n(a) \propto a^{-2.5}$  with minimum and maximum grain radius of 0.005  $\mu\text{m}$  and 5 cm, respectively. If this is indeed the case, one needs to revise upward the estimated disk mass of CQ Tau by a factor of about 6, to compensate for the corresponding decrease of the opacity (D’Alessio et al. 2001). The disk mass is then approximately 6% of the stellar mass. This is a rather large value, but not exceptionally so (Natta et al. 2000).

Calvet et al. (2002) have used the D’Alessio et al. (2001) models to investigate the properties of the T Tauri star TW Hya, which has a millimeter spectral index  $\alpha \sim 2.4$ , practically identical to that of CQ Tau, and is also resolved at 7 mm (Wilner et al. 2000). They find that the grains in the outer disk of TW Hya must have grown to sizes of  $\sim 1$  cm, and that the disk has a mass of about 0.06  $M_{\odot}$ , i.e., 10% of the stellar mass. The profile of scattered light at 1.1 and 1.6  $\mu\text{m}$  indicates that the disk is flared, rather than geometrically thin (Weinberger et al. 2002).

The similarities between CQ Tau and TW Hya are striking. Both objects seem to have flared disks, where gas and dust have to be well mixed; grains have certainly been processed, and the original size distribution has been significantly altered, but their outer disks retain the main features of youth. Models of the evolution of grains in the solar nebula predict a first phase where grains grow and simultaneously settle on the disk midplane by collisional coagulation, controlled by the drag of the gas in the disk (see Weidenschilling 2000 and references therein). The typical outcome (Weidenschilling 1997) is a concentration of solids in the midplane, with about 1/2–1/3 of the original dust mass in large bodies (diameter  $> 1$  km) and a tail of smaller bodies distributed between the initial size (1  $\mu\text{m}$ ) and a maximum of about few metres. A small fraction of the grains may be easily stirred by turbulence to higher altitudes than predicted, providing the opacity (to the stellar radiation) necessary to keep the disk flared. Given the many

uncertainties, these results are at least qualitatively consistent with the analysis of millimeter data for CQ Tau and TW Hya.

A problematic aspect is that both CQ Tau and TW Hya are rather “old” pre-main-sequence stars, with estimated ages of about 10 Myr. The timescale of the collisional coagulation process is typically a few thousands times the Keplerian period, i.e.,  $\lesssim 10^6$  yr at 100 AU from CQ Tau. After this time, one can expect further evolution to occur, clearing the gaseous disk and depleting further the population of small solids (Lagrange et al. 2000 and references therein). It is possible that in the outer disk collisional coagulation proceeds much more slowly than currently estimated, due, e.g., to slow-decaying turbulence or to a sticking probability much lower than assumed (Beckwith et al. 2000 and references therein). Until calculations that explore these (or other) possibilities are performed, it will be difficult to understand the exact implications of the observational results on grain growth in the outer disks of pre-main-sequence stars that are now becoming available.

## 5. Conclusions

We present new subarcsecond resolution 7 mm observations that clearly resolve the dusty disk surrounding the 10 Myr old 1.5  $M_{\odot}$  pre-main-sequence star CQ Tauri, and we investigate millimeter observations from 1.3 mm to 7 mm using a two-layer flared disk model. The main conclusions are:

1. The 7 mm emission is resolved in approximately the north-south direction, with aspect ratio that implies an inclination of about 70 degrees, in good agreement with that derived from polarimetric and photometric variability (Natta & Whitney 2000).
2. The resolved size of the 7 mm emission rules out the possibility that the millimeter spectral index of  $\sim 2.4$  can be accounted for by optically thick emission.
3. The comparison of the millimeter data with disk models shows that the mean dust opacity in the outer disk has a wavelength dependence  $\kappa \propto \lambda^{-0.6 \pm 0.1}$ . The observations are not consistent with a steeper power law dependence, such as found in ISM dust, nor with a grey opacity, as expected if the particles were much larger than the wavelengths of the observations. This result does not depend critically on any of the model parameters, since the dust emission is almost entirely optically thin.
4. The most likely interpretation of the shallow millimeter spectral index is that the dust particles have grown to sizes much larger than the sub-micron ones typical of the ISM. A mixture of grains of different sizes and composition with  $n(a) \propto a^{-2.5}$  and maximum size of few centimeters can reproduce the observation (Miyake & Nakagawa 1993; D’Alessio et al. 2001). The evidence for grain growth and evolution is clear.
5. The CQ Tau millimeter opacity law is similar to that in TW Hya (Calvet et al. 2002). Both CQ Tau and TW Hya have ages of about 10 Myr, and one expects that their disks have evolved significantly. In fact, it is somewhat surprising to find that they have not evolved more, as predicted by current models of disk evolution and planet formation (Ruden 1999). It is clear that calculations that explore more extensively a larger parameter space are required. Here we can only stress that, at present, spatially resolved multi-wavelengths millimeter observations provide the best observational constraint for models of the early stages of the evolution of the dusty disk.

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## References

- D’Alessio, P., Calvet, N., & Hartmann, L. 2001, *ApJ*, 553, 321  
 Beckwith, S. V. W., Henning, T., & Nakagawa, Y. 2000, in *Protostars and Planets IV*, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: University of Arizona Press), 533  
 Beckwith, S. V. W., & Sargent, A. I. 1991, *ApJ*, 381, 250  
 Butner, H. M., Natta, A., & Evans, N. J. II 1994, *ApJ*, 420, 326  
 Calvet, N., D’Alessio, P., Hartmann, L., et al. 2002, *ApJ*, 568, 1008  
 Chiang, E. I., & Goldreich, P. 1997, *ApJ*, 490, 368  
 Chiang, E. I., Joungh, M. K., Creech-Eakman, M. J., et al. 2001, *ApJ*, 547, 1077  
 Dullemond, C. P., Dominik, C., & Natta, A. 2001, *ApJ*, 560, 957  
 Dullemond, C. P., van Zadelhoff, G. J., & Natta, A. 2002, *A&A*, 389, 464  
 Dullemond, C. P., & Natta, A. 2003a, *A&A*, in press  
 Dullemond, C. P., & Natta, A. 2003b, *A&A*, in press  
 Dutrey, A., Guilloteau, S., Duvert, G., et al. 1996, *A&A*, 309, 493  
 Hildebrand, 1983, *QJRAS*, 24, 267  
 Kikuchi, N., Nakamoto, T., & Ogochi, K. 2002, *PASJ*, 54, 589  
 Kitamura, Y., Momose, M., Yokogawa, S., et al. 2002, *ApJ*, 581, 357  
 Lagrange, A.-M., Backman, D. E., & Artymowicz, P. 2000, in *Protostars and Planets IV*, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: University of Arizona Press), 639  
 Mannings, V., & Sargent, A. I. 1997, *ApJ*, 490, 792  
 Mannings, V., & Sargent, A. I. 2000, *ApJ*, 529, 391  
 Miyake, K., & Nakagawa, Y. 1993, *Icarus*, 106, 20  
 Mundy, L. G., Looney, L. W., Erickson, W., et al. 1996, *ApJ*, 464, L169  
 Natta, A. 1993, *ApJ*, 412, 761  
 Natta, A., Grinin, V. P., & Mannings, V. 2000, in *Protostars and Planets IV*, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: University of Arizona Press), 559  
 Natta, A., Prusti, T., Neri, R., et al. 2001, *A&A*, 371, 186  
 Natta, A., & Whitney, B. A. 2000, *A&A*, 364, 633  
 Natta, A., & Whitney, B. A. 2001, *A&A*, 371, 186  
 Pollack, J. B., Hollenbach, D., Beckwith, S., et al. 1994, *ApJ*, 421, 615  
 Ruden, S. P. 1999, in *The Origin of Stars and Planetary Systems*, ed. C. J. Lada, & N. D. Kylafis (Dordrecht: Kluwer Academic Publishers), 643  
 Testi, L., Natta, A., Shepherd, D. S., & Wilner, D. J. 2001, *ApJ*, 554, 1087  
 Weidenschilling, S. J. 1997, *Icarus*, 127, 290  
 Weidenschilling, S. J. 2000, *SSRv*, 92, 295  
 Weinberger, A. J., Becklin, E. E., Schneider, G., et al. 2002, *ApJ*, 566, 409  
 Wilner, D. J., Ho, P. T. P., Kastner, J. H., & Rodríguez, L. F. 2000, *ApJ*, 534, L101  
 Wolf, S. 2003, *ApJ*, 582, 859