EFFECTS OF DUST GROWTH AND SETTLING IN T TAUΡI DISKS

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Received 2005 August 16; accepted 2005 October 12

ABSTRACT

We present self-consistent disk models of T Tauri stars that include a parameterized treatment of dust settling and grain growth, building on techniques developed in a series of papers by D’Alessio et al. The models incorporate depleted distributions of dust in upper disk layers along with larger sized particles near the disk midplane, which are expected theoretically and, as we suggested earlier, are necessary to account for millimeter-wave emission, SEDs, scattered light images, and silicate emission features simultaneously. By comparing the models with recent mid- and near-IR observations, we find that the dust-to-gas mass ratio of small grains at the upper layers should be < 10% of the standard value. The grains that have disappeared from the upper layers increase the dust-to-gas mass ratio of the disk interior; if those grains grow to maximum sizes of the order of millimeters during the settling process, then both the millimeter-wave fluxes and spectral slopes can be consistently explained. Depletion and growth of grains can also enhance the ionization of upper layers, increasing the possibility of the magnetorotational instability for driving disk accretion.

Subject headings: accretion, accretion disks — circumstellar matter — stars: formation — stars: pre–main-sequence

Online material: color figures

1. INTRODUCTION

It is commonly accepted that disks around T Tauri stars are mostly heated by stellar radiation intercepted by the flared surfaces of these disks (Kenyon & Hartmann 1987, 1995). A large fraction of the intercepted radiation is deposited in the disk upper atmosphere, which becomes hotter than deeper layers, producing spectral features in emission, such as the observed silicate bands (Calvet et al. 1991, 1992; Chiang & Goldreich 1997; D’Alessio et al. 1998; Natta et al. 2000). Stellar radiation is absorbed by dust grains in the disk, which reemits the energy at longer wavelengths. Analyses of the spectral energy distributions (SEDs) combined with disk structure calculations thus provide information on the properties and state of the solid particles in the disk.

The flat slopes of the SEDs at millimeter wavelengths, indicative of grains larger than those in the interstellar medium (ISM), have suggested dust evolution in T Tauri disks for some time (Beckwith et al. 1990; Beckwith & Sargent 1991; Miyake & Nakagawa 1993; Pollack et al. 1994, hereafter P94). Interpretation of scattered light images in the optical and near-IR provides additional evidence for grain growth (Cotta et al. 2001; D’Alessio et al. 2001; Watson & Stapelfeldt 2004).

In a series of papers (D’Alessio et al. 1998, 1999, 2001; hereafter Paper I, Paper II, and Paper III, respectively), we have developed physically self-consistent models of T Tauri accretion disks and explored observational predictions based on these models. They include both viscous dissipation and heating by irradiation from the central star. The disk structure is solved iteratively, as the vertical disk thickness depends on the irradiation heating, which in turn depends on the vertical structure. Changes in the dust opacity affect the vertical disk structure and therefore the temperature and density distribution as a function of both radius and height.

In Paper II we showed that models in which the disk has dust like that inferred for the diffuse ISM (i.e., silicates and graphite grains, with abundances and optical properties from Draine & Lee [1984, hereafter DL84]) and a maximum grain radius \( a_{\text{max}} \approx 0.25 \mu m \) uniformly mixed with the disk gas (well-mixed models) fail to explain detailed observations. Specifically, the models exhibit too little millimeter-wave emission and larger far-infrared fluxes than observed from typical classical T Tauri stars (CTTSs) for reasonable disk masses; the models are too geometrically thick in the direction perpendicular to the midplane, which results in wider dark lanes in scattered light images of edge-on disks than observed; and the models predict too large a fraction of stars extinguished by their disks than observed in surveys, assuming a random distribution of inclinations.

Motivated by the need to improve the agreement with observations, in Paper III we considered the effects of changing dust properties in well-mixed models. We showed that well-mixed models in which dust grain radii \( a \) follow a power-law distribution \( n(a) \propto a^{-p} \), \( 2.5 \leq p \leq 3.5 \), with a maximum grain radius \( a_{\text{max}} \approx 1 \) mm, can explain the above observational constraints. Grains bigger than typical ISM dust grains affect both the long- and short-wavelength predicted properties of the dust mixture; larger grains yield a larger millimeter-wave emissivity and spectral indices in better agreement with observations. At the same time, the number of small grains is reduced to account for the mass locked up in large grains, and this decreases the optical and near-infrared opacity. This results in less absorption of stellar flux, lower disk temperatures, and a decreased IR emission. Similarly, the predicted dark lanes in scattered light images of edge-on disks are narrower, and the expected number of heavily extincted stars becomes consistent with observations. However, since big grains have a gray opacity at wavelengths much shorter than their sizes, such disk models predict no silicate emission bands.

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