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Dust growth and setting in protoplanetary disks and radiative transfer calculations

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ABSTRACT

We produced the spectral energy distribution (SED) and the millimetre intensity images of laminar disks by means of radiative transfer calculations to evaluate how the dust growth and settling affect the observed results. We examined two cases at $t=4300$ and 25 000 yrs, when a dust dominant layer forms at the radial positions of 5.2 AU and 30 AU, respectively. In these regions, the dust particles grow ~6 cm and ~250 μm in the dust dominant layers with a geometrical thickness of 1.5×10^{-5} and 0.016 times the gas scale height. The SED shows a shallow flux slope in the millimetre wavelengths, which is due to thermal emission from submillimetre-sized dust in the several tens AU region. In face-on cases, a triangle-shaped emission feature is also detected in 10 μm, which is attributed to small ($\lesssim$micron – sized) silicate dust floating at the disk surface. In the millimetre intensity images, the dust dominant layer is traced with the thermal emission from the large particles. The spatial distribution of large grains is seen in the image of $d\log I_\nu/d\log\nu-2$, which corresponds to a spectral opacity index. The value is low as <2 towards the dust dominant layer, even if the optical depth is low. Although detailed analyses are essential to estimate the physical parameters such as the particle sizes and the dust density distribution, we expect that the evidence for the dust growth and settling is obtained from the real observed data.

1. Introduction

It was about 40 years ago when the pre-solar nebula models were proposed. Safronov (1969) and Hayashi et al. (1985) have developed the minimum-mass solar nebula (MMSN), in which planets form by accretion of the nebula material of the minimum mass. According to the standard planet formation scenario, the dust growth and settling is the first step, which we focus on in this work. While the gas and dust orbit around the star, the dust particles grow in size by mutual collisions (Weidenschilling, 1984; Mizuno, 1989; Miyake and Nakagawa, 1993). Along with the dust growth, the particles sediment around the disk midplane because of the vertical gravity force, forming a geometrically thin, dust layer. In a classical theory, if the settling progresses as a local density exceeds the Roche density, the dust layer can fragment by gravitational instability, then planetesimals form (Goldreich and Ward, 1973). However, protoplanetary disks are actually turbulent because of thermal convection (Lin and Papaloizou, 1980), vertical shear motion (Cuzzi et al., 1993; Weidenschilling and Cuzzi, 1993), and magneto-rotational instability (Balbus and Hawley, 1991). The turbulence plays some roles in the disks. It increases the collisional rate of dust (Völk et al., 1980). On the other hand, it stirs up particles, when the Stokes parameter, the ratio of the stopping time to the eddy turnover time, is less than unity, which prevents formation of a dust layer (Cuzzi et al., 1993). Although the dust particles eventually sediment towards the midplane and the planetesimals form in there, the detailed pathway of planetesimal formation is more complex than that was thought before.

Several observational evidence for the dust growth has been reported so far. One of pioneering work is the detection of flux excess in T Tauri stars in the submillimeter and millimetre wavelength ranges (Beckwith and Sargent, 1991; Miyake and Nakagawa, 1993). Assuming that the observed flux is dominated by thermal emission from the circumstellar disks and it is in optically thin regime, the observed flux, F_ν, can be approximated to be $F_\nu\approx M_{\rm disk}k_\nu B_\nu(T_d)/D^2$, where $M_{\rm disk}$, k_ν, $B_\nu(T_d)$, and D are the dust disk mass, the mass absorptive opacity, the blackbody radiation function at temperature T_d, and the distance to the object, respectively. In these wavelength ranges, the blackbody radiation is in the Rayleigh–Jeans regime, i.e. $B_\nu(T_d)\approx(2k_BT_d/c^2)\nu^2$ for typical disk temperature of 100 K, where k_B and c are Boltzmann's constant and speed of light, respectively. In addition, the dust opacity can be fit with a power function, i.e. $\kappa_\nu\approx\kappa_0(\nu/\nu_0)^\beta$. Hence, $F_\nu\propto\nu^{\beta+2}$ if the spectral flux index, $\alpha\equiv d\log F_\nu/d\log\nu$, is introduced, $\alpha=\beta+2$.

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Although the absolute dust opacity in the disk cannot be directly obtained from the observations, its spectral slope β can be easily estimated. For the interstellar dust, where is in the Rayleigh limit ($a > \lambda$), $\beta_{\rm ISM}$ is close to 1.7–2 (Draine, 2006, and references therein). This value attains down to ~ 0 in the large particles in the geometrical optics regime ($a > \lambda$). For the particles with a power-law size distribution function, $n(a) \propto a^{-p}$, β is found to be $\sim (p-3)\beta_{\rm ISM}$ for the maximum size $a_{\rm max} \gtrsim 3\lambda$ (Draine, 2006). Low $\beta < \beta_{\rm ISM}$ values have been detected in many T Tauri stars and Herbig Ae/Be stars (e.g. Kitamura et al., 2002; Andrews and Williams, 2005; Lommen et al., 2010). This suggests the dust growth in the protoplanetary disks in these object classes. It should be noted that the actual spectra depend not only on the particle sizes but also on some other factors such as the chemical composition, the temperature, and the shape (e.g. Pollack et al., 1994; Mennella et al., 1998; Imai et al., 2009; Mutschke et al., 2013). Low β values themselves do not guarantee the dust growth, hence this is valid when the factors other than the particle size do not change much.

In contrast, the evidence for the dust settling has been hardly detected. Even though the dust dominant layer, in which the dust mass density exceeds the gas density, is present in disks, since the thickness is expected to be significantly thinner than the gas scale height, this cannot be directly resolved using the current telescopes. Besides this, other signs that suggest planet formation in the protoplanetary disks have been obtained. One interesting point is the detection of transitional disks or inner holes in T Tauri stars and Herbig Ae stars (e.g. Calvet et al., 2002, 2005; Espaillat et al., 2007; Isella et al., 2010; Andrews et al., 2011). The inner radii in these objects have been estimated to be, for example, 4 AU for TW Hya (Calvet et al., 2002), 10 AU for CoKu Tau/4 (D'Alessio et al., 2005), 14 AU for RY Tau (Isella et al., 2010), and 24 AU for GM Aur (Calvet et al., 2005). These are significantly larger than the sublimation radii ($\sim$0.1 AU) in these object classes. There are three physical reasons for this. One is less density in the inner region. This is interesting because such a gap can be produced by sweeping up the dust and gas material when giant planets form (e.g. Lin and Papaloizou, 1986; Bryden et al., 1999). Another is due to reduction of the dust opacity by dust growth. Although the opacity of large particles increases with increasing the size in the far-infrared or longer wavelength ranges, it decreases for $a \gtrsim 1$ cm (see Section 2). Hence, one can suggest the presence of pebble sized or larger dust close to the central star. The other is photo-evaporation (Clarke et al., 2001; Alexander et al., 2006a, 2006b). The radiation from the central star can ionize the gas in the disk surface and drive a wind. The dispersal of the disk material due to this wind becomes important at late times when the accretion rate is below the mass-loss rate.

Meanwhile some attempts to evaluate the appearance of the protoplanetary disks have been carried out (e.g. D'Alessio et al., 2006; Andrews et al., 2011; Sauter and Wolf, 2011; Gräfe et al., 2013). D'Alessio et al. (2006) and Gräfe et al. (2013) performed radiative transfer calculations to produce the SED and images of low-mass protoplanetary disks taking into account for the dust growth and settling. They found that only the interstellar dust population is insufficient to fit the low β, the surface brightness of the optical to near-infrared images, but large and small grains are required near the midplane and at the disk surface, respectively. In these analyses, the dust and disk properties are determined or constrained to fit the observed SED and images. In contrast, attempts to predict the observed results by using theoretical models of the dust growth and settling have also been made (e.g. Dullemond and Dominik, 2004; Birnstiel et al., 2012; Boehler et al., 2013). Birnstiel et al. (2012) considered the coagulation of settling particles in turbulent disks and produced the SED and 880 μm images. They concluded that large inner holes can be produced by a combination of dust growth and other effects to reduce the mass in the inner region.

Both the theory and the observation have rapidly developed in this field. The above-mentioned attempts are useful to provide observational constraints on the theory. In this paper, we reproduce the millimeter flux images and the SED of laminar disks of the MMSN by means of radiative transfer calculations. The aims of our work is to predict and study how the dust dominant layer or the region where large particles exist appear in the observed data. We explain the laminar protoplanetary disk models in Section 2 and the methodology of the radiative transfer calculations in Section 3. In Section 4, we present the results and provide our interpretations on the model results.

2. Protoplanetary disks

We consider a passive protoplanetary disk of a low-mass star with the mass, $M_\star$, of 1 $M_\odot$. The disk is isothermal in the vertical direction and the structure is supported by the gas pressure. With this assumption, the gas mass density, $\rho_{\rm g}(R, z)$, is given by

$$\rho_{\rm g}(R,z) = \frac{\Sigma_0}{\sqrt{2\pi} h_p} (R/1\ {\rm AU})^{-3/2} \exp\left(-\frac{z^2}{2\,h_p^2}\right), \tag{1}$$

where Σ_0 is the surface density coefficient. We set $\Sigma_0 = 1700\ {\rm g\ cm^{-2}}$ for the MMSN (Hayashi, 1981). h_p is the gas scale height, which is given by $h_p = c_s/\Omega_k$. $\Omega_{\rm k}$ is the Keplerian angular velocity, $\sqrt{GM_\star/R^3}$, where G is the gravitational constant. c_s is the sound speed, $\sqrt{k_B T/(\mu m_\mu)}$, where T, μ, and m_μ are the disk temperature, the mean molecular weight, where we set $\mu = 2.34$, and the atomic mass unit, respectively. For the disk temperature, we apply $T = 280(R/1\ {\rm AU})^{-1/2}$.

We examine a laminar disk that was analysed by Nakagawa et al. (1986). The dust particles settle with the vertical velocity, $V_{\rm z} = -z\Omega_k^2/A\rho_g$. We assume that Epstein's law, i.e. the friction coefficient, A, is given by $A = c_s/\rho_s a$, where ρ_s is the bulk density of the dust particle, since the particle sizes are mostly smaller than the mean free path length of the gas molecules. The dust particles grow by coagulation. Hence, they should have fluffy structures (e.g. Okuzumi et al., 2012; Kataoka et al., 2013). However, for simplicity, we assume that the dust particles are homogeneous compact spheres with the DL-type chemical composition (Draine and Lee, 1984).

We evaluate the dust settling path at $R = 5.2$ AU, 10 AU, 30 AU, and 100 AU at two temporal evolutions at $t = 4300$ (model 1) and 25 000 yrs (model 2). At these times, the particles reach the vertical position, at which the dust density ρ_d attains the gas density, implying that a dust dominant layer forms, at $R = 5.2$ AU and $R = 30$ AU, respectively. Nakagawa et al. (1986) divided the settling path into four phases. The particles move phases A–D from the initial vertical position at $z = z_g = (\sqrt{\pi}/2)h_p$. Phases A and B are in the upper, gas-dominant layer, where $\rho_g > \rho_d$. Phases C and D are in the dust-dominant layer, where $\rho_d > \rho_g$. In both layers, there is a turning point where the velocity component dominates in the vertical component (phases A and C) to the radial component (phases B and D). The vertical positions are labeled as z_1–z_3 at the borders between the adjacent phases and z_4 at the bottom of phase D.

At $t = 4300$ yrs, although the particles reach $z = z_2$, at $R = 5.2$ AU, they do not reach even at the border between phases A and B, i.e. $z = z_1$, at $R \geq 10$ AU. The settling paths are calculated as follows. By integrating $dt = dz/V_{\rm z}$, we have

$$t = \frac{16}{\pi} \frac{\Sigma_0}{\Sigma_d} \frac{1}{\rho_s \Omega_k (1 + a_0/a_s)} \ln\left(\frac{a z_g}{a_0 z}\right), \tag{2}$$