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Dust Trapping and Coagulation in Protoplanetary Disks

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Abstract. In this work, we carry out two-fluid (gas+dust) hydrodynamical simulations on a large family of models in order to study the dust coagulation and the dust-gas dynamical processes in protoplanetary disks. Our theoretical effort is guided by the observational results of disks in nearby star forming regions at sub-millimeter and millimeter (mm) wavelengths. By a systematic comparison with the continuum emission at several mm bands from ALMA observations, we find that ringed structures are predicated in the unresolved faint disks for those with mm spectral indexes as low as about 2.0. Our parameter exploration can also be used to constrain the fragmentation velocity, one key parameter of the dust coagulation model, and some other disk parameters.

Keywords. planetary systems: protoplanetary disks — planets: rings — submillimeter

1. Introduction

The discovery of thousands of exoplanets over the last couple of decades has clearly shown that the birth of planets is a very efficient process in nature (e.g., Burke *et al.* 2015). The commonly accepted theory is that planets form in young disks orbiting Pre-Main Sequence stars through the agglomeration of small dust particles into km-sized "planetesimals", which are massive enough to gravitationally attract other solids in the disk (see review by Chiang & Youdin 2010). Grain growth from sub-micrometer sizes, which are the typical sizes of dust in the interstellar medium (ISM), to millimeter and centimeter sizes is thus the first step toward the formation of planetesimals inside young circumstellar disks. However, models of the evolution of disks solids with density and temperature both decreasing with distance from the central star have predicted radial drift timescales which are too short (e.g., only $100 \sim 1000$ orbits) to form planetesimals (see review by Johansen *et al.* 2014). It is generally believed that some disk substructures have to be invoked to slow down the dust radial drift because of the positive pressure gradient in the inner edge of the bump.

Motivated by the low mm spectral indexes $\alpha_{\rm mm}$ observed for a large sample of protoplanetary disks (PPDs) in several nearby star forming regions (Ricci *et al.* 2012; Ansdell *et al.* 2018; Andrews *et al.* 2018), we take a local maximum substructure for the gas surface density profile, which is assumed to be generated by a gap in the disk viscosity. By performing detailed simulations for two fluids (gas+dust) hydrodynamics, we study the dust trapping and coagulation processes in the disks and then calculate the dust continuum emission at several mm bands with detailed radiative transfer (Li *et al.* 2019, in preparation). Our main goal is to interpret the low spectral indexes observed for many young disks, and understand the link between the spectral slope and the dust dynamics in the disks. Based on this diagnostics, we can constrain some fundamental parameters for

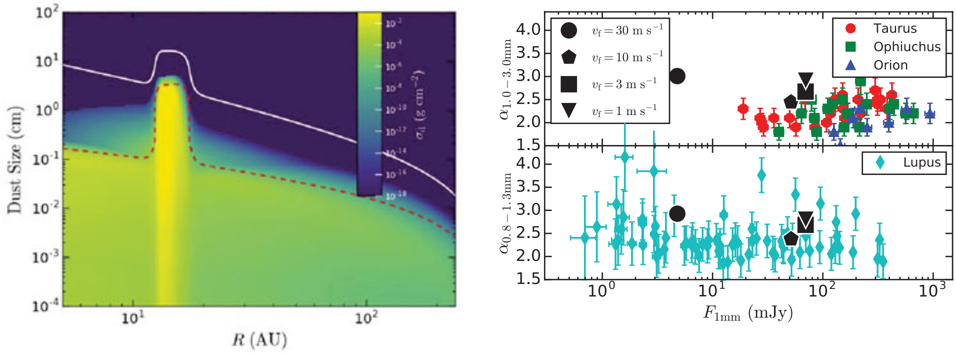

Figure 1. Left: dust surface density distribution for different dust species at the time 2.1 Myr for a typical model. The red dashed line indicates the fragmentation barrier, which represents the maximum size of the particles before they reach fragmentation velocities. The white solid line denotes the grain size corresponding to a Stokes number of unity. Right: 1 mm flux $F_{1\text{mm}} - \alpha_{\text{mm}}$ plot for models with different fragmentation velocities. The observed fluxes are all normalized with a disk distance of 140 pc and extrapolated to 1 mm based on the observed spectral indexes (Ricci *et al.* 2012; Ansdell *et al.* 2018). The spectral indexes are calculated between 1.0 mm and 3.0 mm (upper panel), and between 0.89 mm and 1.33 mm (lower panel).

the dust coagulation model and shed new insight into the mechanism of dust trapping and growth.

2. Results

We present detailed hydrodynamical simulations for PPDs to study the two-fluid co-evolution with self-consistently considering dust coagulation/fragmentation processes (for previous version of the code, see Li *et al.* 2005; Birnstiel *et al.* 2010a). We then compare the dust continuum emissions produced from *RADMC-3D* (Dullemond *et al.* 2012) with multi-wavelength data. By assuming a viscosity gap in the inner region of the disk, a gas bump can be generated, which results in an effectively dust trapping in the same region. With a systematically parameter study for different model parameters (e.g., the fragmentation velocity v_f, gas surface density, disk global viscosity α_0, viscosity gap parameters, disk scale height, and disk gas profile index), we can quantify the role of the viscosity gap in the mm dust continuum spectral index.

Our main conclusions are summarized as follows (Li et al. 2019, in preparation). 1) Gas bump is necessary to produce a lower spectral index. Such a gas bump could facilitate the trapping of the dust particle and also make efficient dust size growth (left panel of Figure 1). 2) Our model with a reasonable v_f ($3 \sim 10$ m s^{-1}) can reproduce a low α_{mm} close to 2.0 (right panel of Figure 1). The tentatively negative relation between α_{mm} and $F_{1\text{mm}}$ obtained from Ansdell *et al.* (2018) for the faint PPD sources can be explained by a relatively low v_f ($\lesssim 10$ m s^{-1}) with a variation of dust mass surface density. This is simply because the optical depth becomes smaller as the dust mass (mm flux) decreases. 3) α_{mm} is not very sensitive to the gas bump width, gap depth, disk scale height, and disk profile index. Even though one ringed structure in the outer region of the disk can produce a slightly brighter disk, our one ringed-structure model can hardly reproduce the bright end disks with the low spectral index from previous surveys. We expect that multiple rings can be responsible for such very bright disks.

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