Evolution of dust surface density distribution in protoplanetary disks: Effect of grain growth and fragmentation

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It is widely accepted that planets form by accumulation of dust entrained in gaseous circumsteller disks (protoplanetary disks). Of particular interest is thus the spatial distribution of dust in the disks as the initial conditions of planet formation. Recently, high angular resolution observations of dust thermal emission at (sub-)millimeter wavelengths have constrained the radial distribution of the dust surface density in the outer regions of the disks (where the distance from the central star is larger than 100 AU). For disks around T Tauri stars, the resolved disk images are well fitted by a radial power law in dust surface density with a typical power law index of -0.7 to -1 (Williams and Andrews 2007). The dust surface density roughly proportional to r^{-1} is often interpreted in terms of an irradiated viscous accretion disk (Hartmann et al. 1998), assuming that dust is tightly coupled to gas. If this model holds even in the inner regions, however, the dust surface density becomes too small to form planets.

Analyses of the spectral energy distributions at (sub-)millimeter wavelengths suggest that dust grains have grown to at least millimeter size in many T Tauri disks (D'Allesio et al. 2006). These grains are too large to be completely coupled to gas and subject to inward drift due to gas drag. Thus, the evolution of the dust surface density would be significantly different from that of the gas surface density. In this study, we explore the effect of grain growth on the evolution of the dust surface density in a protoplanetary disk because the radial motion of dust strongly depends on the grain size. Instead of solving the coagulation equation, we develop an analytical model of the size evolution of the largest dust grains, in which the total dust mass is always concentrated, at any given time and location in the disk. We also include the effect of collisional fragmentation in a simple manner; i.e., dust growth stops when the collision velocity induced by gas turbulence (also an increasing function of the grain size) exceeds a threshold (Blum and Wurm 2008). The purpose of this study is to examine whether the observation can be reproduced in our model, and to predict the dust surface density in the inner region of the disk.

Here we summarize a typical behavior of dust evolution: Initially, dust grains are so small that they grow moving tightly coupled to gas. The duration of this epoch is relatively short (several 10^5 yr) even in the outer region of the disk. Once the largest grains have reached to mm in size, further growth is prevented by rapid inward drift in the outer region of the disk. Then the grains size is fixed at mm because of a competition between grain growth and grain loss due to the inward drift. We find that the resulting dust surface density in this region is proportional to r$^{-3/4}$, which is consistent with the observation. In contrast, collisional fragmentation inhibits grain growth at cm-size in the inner region where the time scale of grain growth is much shorter than the outer region. In this case, the inward dust mass flux increase with r leading to the “traffic jam” of dust. This effect enhances the dust surface density in the inner region, and the dust surface density required to form planet is achieved in some initial conditions. We also find the radial profile of the dust surface density becomes proportional to r$^{-3/2}$. This profile is similar to that of the well-known minimum mass solar nebula model (Hayashi 1981).