A dust accumulation process caused by dust radiative cooling

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Introduction: Dust particle accumlation in the protoplanetary disk is an important process to form planetesimals as well as asteroids. To understand a physical process of the accumulation, we investigate a possible mechanism triggered by dust radiation cooling. In this study, we carry out hydrodynamic linear stability analysis of 1-dimensional gas-dust fluid system under an effect of radiative cooling.

A physical picture examined in this study is as follows. In a fluid system consisting of gas and dust particles, the main cooling mechanism is the radiative cooling from dust particles. When the cooling caused by dust takes place effectively in a region, the gas temperature and the pressure decrease at the region. Because of the gas pressure gradient, a gas flow converging to the region is driven. Dust particles are entrained in the gas flow due to the gas drag force, and they converge to the region as well. Then the dust particle number density there is enhanced, and the cooling rate of the region can be raised too, because the cooling rate is proportional to the dust number density. This process would increase the dust number density.

Linear Stability Analysis: Hydrodynamic linear stability analysis is a way to investigate the response of a given fluid system against a perturbation. We represent a perturbation as small fluctuations of physical quantities from an equilibrium state. These small deviations evolve following equations of fluid dynamics. Perturbations are represented as a plane waveform. This form is useful to find a solution of equations and its super-position can represent a time evolution of any perturbation. When the angular frequency of the plain wave solution is imaginary number and its imaginary part is positive, this solution means exponential growth of the perturbation with time. Then the system is unstable against the perturbation. Dust density perturbation growth means the increase of the dust density, namely dust accumulation. Although this analysis is valid only when deviations are small, it can describe a first stage of dust accumulation process.

Model: As the equilibrium state we consider an ideal situation in this study, because it is clearer to understand the physical process. We assume that the system is spatially uniform, static, and the gas temperature is higher than the dust temperature. For retaining this state, we introduce a hypothetical heat function for the gas, which is a function of the gas temperature and the gas density. We do not specify any realistic cause of the heat now. As the cooling mechanism of the system, the radiation from dust particles is taken into consideration. It is assumed that the radiation leaves the system without being absorbed again for simplicity. Because of the difference of temperatures between gas and dust, thermal energy is transferred from the gas to the dust particle by gas-dust collisions. We can neglect a heating effect of drag force caused by gas-dust relative velocity in this analysis because velocity perturbation is small. We assume that the gas and the dust particles are coupled by drag force dynamically. Gas experiences drag force and self pressure gradient. We neglect dust pressure gradient, therefore dust experiences only drag force.

Results and Summary: As a result of our linear analysis, we obtain a dispersion relation, which is a relation between the angular frequency and the wave number of a plane wave solution. We find that when the gas temperature derivative and the gas-density derivative of the heat function satisfy certain criteria, an unstable mode emerges. When the instability takes place, the fluctuation of the dust particle number density grows. It means a dust accumulation occurs in the linear regime.

If a realistic heat function meets the obtained criteria, a dust accumulation may occur in a protoplanetary disk. And this accumulation may lead to the planetesimal formation.

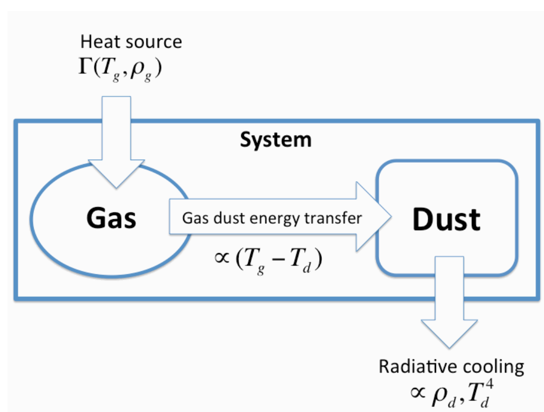

Figure 1: Energy flow in the gas-dust system.