Secular Gravitational Instability of a Dust Layer in Shear Turbulence

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In the standard scenario of planet formation, planetesimals are the precursors of planets, the sizes of which are on the order of kilometer. Their formation process is one of the unsolved problems of the planet formation theory. From micron-sized dust grains dust particles grow to centimeter size in a protoplanetary disk by collisional agglomeration. The least understood growth phase is growth from centimeter-sized dust to kilometersized planetesimals.

One of the possible models in this stage is the gravitational instability model. A very thin and dense layer of settled dust aggregates in the mid-plane of the protoplanetary disk may be gravitationally unstable. Then the gravitational collapse of the dust layer occurs, and kilometer-sized planetesimals are formed directly. This scenario has the advantage of a very rapid formation timescale, which is on the order of the Keplerian time. However, the various hydrodynamic instabilities cause the turbulence in the protoplanetary disk. In this case, the gravitational instability may be suppressed since the dust layer can not become thin due to the turbulence [1].

We investigated the motion of dust particles in turbulent gas and derived the surface density evolution using the stochastic model [2]. We derived the advection diffusion equation with the strong coupling approximation. We solved the advection diffusion equation coupled with the Poisson equation for gravity using the linear approximation. As a result, we found that the dust layer is always unstable regardless of the turbulence strength, but its timescale becomes longer as the turbulence becomes stronger. The dust density increases monotonically because of the instability.

The physical meaning of the secular gravitational instability can be understood in terms of the responses to the density perturbation. We suppose that the density fluctuation exists. The gravitational potential is induced by the density fluctuation. Due to the resultant potential gradient, the matter moves to the local maximum point of the surface density with the terminal velocity. Therefore, the density fluctuation increases monotonically.

We applied this instability to the protoplanetary disk. This instability always occurs, but its timescale is typically very long. If the radial drift of dust particles due to gas drag is faster than the secular gravitational instability, the secular instability seems to be inefficient. In this case, the particle pileup mechanism due to the radial drift enhances the surface density of dust [3]. Thus, we should compare the timescales of the secular gravitational instability and the radial drift. Figure 1 shows the critical f_g value, where f_g is the enhancement factor of the surface density of gas, as a function of the distance from the Sun. The value J_c is the critical Richardson number. Here we assume the quasi-equilibrium shear turbulence model. If f_g is larger than the critical value, the secular gravitational instability is faster than the radial drift. When $f_g > 3$ and $J_c = 0.1$, the secular gravitational instability is faster than the radial drift in the entire disk. If this condition is satisfied, axisymmetric high-density patterns form. When the dust surface density becomes large due to this instability, the classical gravitational instability may occur finally [4]. We will investigate this process by numerical simulations in the future work.

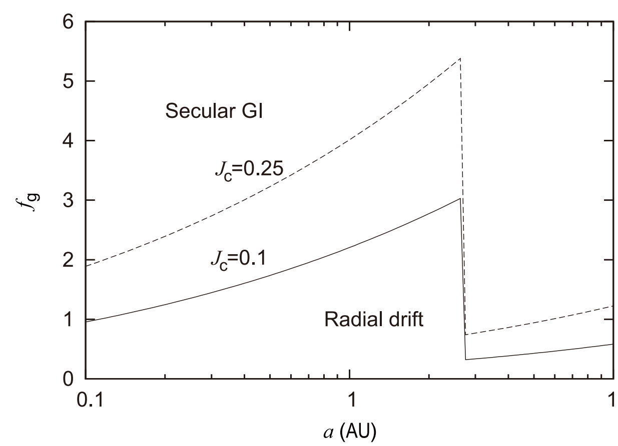

Figure 1: The critical f_g values as a function of the distance from the Sun a.

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References

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