Effects of Gas-Drag Force and Dynamical Friction on the Orbital Instability of a Protoplanet System

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We have investigated numerically the orbital instability of a protoplanet system while taking account of the gas-drag force due to the solar nebula or the dynamical friction with a swarm of planetesimals. Through the long term orbital calculations, we obtained the instability time of a protoplanet system under the gas-drag effect or the dynamical fricition and found that the instability time suddenly becomes large, in other words, the orbital instabilty does not occur practically when the initial orbital separation distance is larger than a certain critical separation distance. Furthermore, we showed that the critical separation distance can be described semi-analytically as a function of the surface density of the nebular gas or planetesimals.

The recent works on the planetary formation show that at the final stage of the planetary accretion, several tens of protoplanets whose masses are of the order of Martian mass are formed through a succesive accretion of planetsimals in the terrestrial planet region (Wetherill and Stewart 1989, Kokubo and Ida 1998,2000). In this stage, the protoplanets would interact with their neighbors through the mutual gravity and, for a long term, they would happen to be transformed to the quitely different orbits or to collide each other. Through this process (i.e., the orbital instability), the present terrestrial-type planets are formed on widely separated orbits as we observe.

Chambers and Wetherill (1998) calculated the orbital evolution and the growth of protoplanets simultaneously. The system consisted of 20 to 50 planetary embryos with masses of about the Martian mass distributed in the terrestrial planet region (0.5 - 2.0 AU). In their calculation they also took account of the secular perturbation due to Jupiter and Saturn. According to their results, in most cases the terrestrial planets are formed with the results that their masses and semimajor axes correspond to ones of present Venus or the Earth. However, as readily deduced, almost all of the planets formed in these simulations have large eccentricities and inclinations compared with those of the present terrestrial planets.

We should note here that the planetary accretion actually proceeds in the presence of the nebular gas except in the final stage, so that the protoplanets experience a gaseous drag due to the solar nebula. At the same time, the protoplanets suffer from dynamical friction due to a swarm of planetesimals. Generally, such energy dissipation processes lead to a decrease in the eccentricities and inclinations of the protoplanets. If the dissipation is intense, the eccentricities of the finally formed planets may be suppressed to the suitablelevel seen in the present planets. By the decrease in the eccentricities and inclinations, however, the protoplanets must be prevented from the onset of an orbital instability, and the protoplanets will not be able to collide with each other; as a result, the terrestrial planets which we observe now would not be formed. Thus, in order to understand the planetary formation process in the final stage, it is rather important to investigate the influence of the gaseous drag (and the dynamical friction) on the instability time of the multi-protoplanet system.

In the present work, we have investigated numerically the orbital instability of a protoplanet system while taking account of the gas-drag force due to the solar nebula or the dynamical friction with a swarm of planetesimals. Through the long term orbital calculations, we examined the instability time of a protoplanet system under the gas-drag effect or the dynamical fricition and found that in both cases, the instability time suddenly becomes large compared with the instability time in a vacuum space which is obtained in Chambers et al. (1996), in other words, the orbital instabilty does not occur practically when the initial orbital separation distance is larger than a certain critical separation distance. Furthermore, we showed that the critical separation distance can be described semi-analytically as a function of the surface mass density of the nebular gas or planetesimals.