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Collisional Fragmentation in Giant Impact Stages

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Abstract

Earth-like terrestrial planets are formed via giant impacts between Mars-sized protoplanets. Giant impacts totally eject fragments with several Mars masses. The total mass of fragments is much smaller than planets. However, the fragments may be observed as warm debris disks. The brightness of debris disks caused by giant impacts evolves due to collisional cascade among fragments. Therefore, collisional cascade is important for the evolution of fragments produced via giant impacts. Furthermore, the fragments may affect the orbits of planets. We carry out N-body simulations containing planets and fragments caused by giant impacts, taking into account collisional cascades in fragments. We discuss the effects of fragments on planetary orbits and the brightness distribution of debris disks.

1. Giant Impacts and Collisional Cascades

In terrestrial planet formation, Mars-sized protoplanets are formed prior to the gas depletion of protoplanetary disk with a large orbital separation of the order of 10 mutual Hill radii, which consistently explains the early formation of Mars inferred from ^{182}W-^{182}Hf chronometer with the half lifetime of 9 Myr [1]. The gas depletion triggers the long term orbital instability of protoplanets and the collisions between protoplanets produce Earth or Venus sized planets[2], which is called the giant impact stage.

In the giant impact stage, merging or hit-and-run collisions mainly occur (see Fig. 1). Forming planets contain more than 90% of the original total mass of protoplanets. Although only small mass fraction goes into debris, the giant impact fragments may be observed as infrared excesses like warm debris disks (see Fig. 2). Therefore, giant impacts may be observed as debris disks [4, 3].

In the giant impact stage, orbital eccentricities of protoplanets increase as large as 0.1, which induce the orbital crossing between protoplanets, collisions between protoplanets produce Earth-sized planets. Planets formed via giant impacts have eccentricities as large as 0.1, which is much larger than those of Earth or Venus (0.015 and 0.007, respectively). Those eccentricities may be damped via dynamical friction with surrounding planetesimals. However, the surface density of surrounding planetesimals decreases via collisional cascade of the planetesimals [5], which reduce the efficiency of dynamical friction. Therefore, collisional fragmentation is taken into account in the issue.

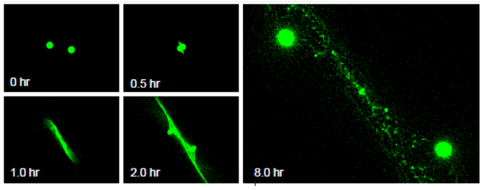

Figure 1: Snapshots of a hit-and-run giant impact, calculated by SPH simulation. This figure comes from Genda et al. (2015)[3].

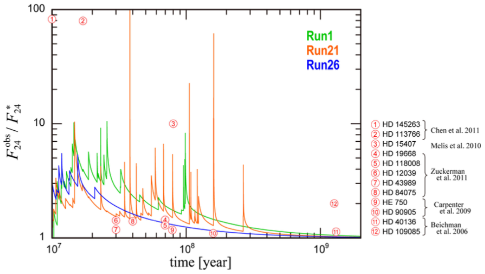

Figure 2: Infrared excesses at 24μm caused by giant impacts, comparing with the excesses observed in debris disks. This figure comes from Genda et al. (2015)[3].

2 N-body simulation with collisional fragmentation

We apply the super-particle approximation for planetesimals and their fragments; a super particle is represented to planetesimals and fragments. Meanwhile, we apply a single particle for a single protoplanet. We integrate the equations of motion of particles via the fourth order Hermite scheme. The orbital integration allows us to accurately treat dynamical evolution and direct collisions between protoplanets and between protoplanets and super particles. However, the number of super particles that we apply is much smaller than that of planetesimals and fragments with which we concerned so that statistical methods are required for accurate calculation of interactions between super particles.

On the other hand, collisional fragmentation between planetesimals are treated statistically using the orbital data of super particles. We calculate the surface density of planetesimals and the average relative velocities around a super particle from the orbits of neighbor super particles. The mass evolution of super particles is obtained from the surface density and relative velocity under the assumption of collisional cascade[5].

We carry out simulations for the orbital evolution of 3 protoplanets with Earth mass $M_\oplus$ in a planetesimal disk with 30 Earth masses composed of 3,000 super particles around the central star with solar mass $M_\odot$. The semimajor axis of the intermediate protoplanet is initially set at 1 AU, the orbital separation of protoplanets is 10 mutual Hill radii, and their eccentricities and inclinations are 0.03 and 0.015, respectively. The radial distribution of super particles is initially put according to $\Sigma(a) \propto a^{-1}$ and their e and i have the Rayleigh distributions with mode values $e = 0.03$ and $i = 0.015$, respectively. The intermediate radius and width of the planetesimal disk are 1 AU and 30 mutual Hill radii, respectively. The collisional cascade is characterized by planetesimal mass $m_{\rm c}$. We set planetesimal mass $m_{\rm c} = 10^{16}$ g (≈ 1 km in radius) for collisional fragmentation, while we have an additional simulation without collisional fragmentation. Fig. 3a,b show the orbital distribution of protoplanets and super particles at $t = 10^3$ year with collisional fragmentation, while Fig. 3c,d are the result without fragmentation. The collisional interaction between protoplanets and planetesimals reduces e and i of planetesimals, while e and i of planetesimals increase. That is caused by dynamical friction. The increase of e and i of planetesimals induce their collisional cascade, which reduce Σ of planetesimals. Collisional fragmentation weakens dynamical friction so that e and i of protoplanets with fragmentation remain higher than those without fragmentation.

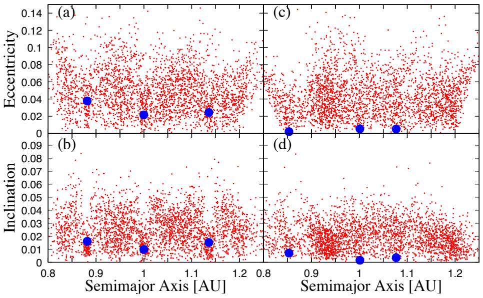

Figure 3: Eccentricities (a,c) and inclinations in radian (b,d) of super particles (red dots) and protoplanets (blue fulled circles) with fragmentation (a,b) or without fragmentation (c,d).

3. Summary and Conclusions

Collisional evolution of planetesimals is important for the orbital evolution of planets in the giant impact stage. The timescale of collisional cascade for planetesimals depends on the size of largest planetesimals. The total mass of collisional fragments ejected from giant impacts is smaller than planetary masses. However, the size of largest fragments may be more than 100km so that the timescale of collisional cascade is 100Myrs or longer. Therefore, the fragments interact planets in such a long timescale that only 0.3 Earth masses fragments may decrease orbital eccentricities of terrestrial planets as small as those of Earth and Venus.

References

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