Formation of Terrestrial Planets from Protoplanets under a Realistic Accretion Condition

KOKUBO, Eiichiro (NAOJ)
GENDA, Hidenori (University of Tokyo)

It is generally accepted that the final stage of terrestrial planet formation is the giant impact stage where protoplanets or planetary embryos formed by oligarchic growth collide with one another to form planets [1,2]. This stage has been mainly studied by *N*-body simulations. So far all *N*-body simulations have assumed perfect accretion in which all collisions lead to accretion. However, this assumption would be inappropriate for grazing impacts that may result in escape of an impactor or hit-and-run. By performing Smoothed-Particle Hydrodynamic (SPH) collision simulations, [3] estimated that more than half of all collisions between like-sized protoplanets do not simply result in accumulation of a larger protoplanet, and this inefficiency lengthens the timescale of planet formation by a factor of 2 or more, relative to the perfect accretion case. The accretion inefficiency can also change planetary spin. [4] found that under the assumption of perfect accretion, the typical spin angular velocity of planets is as large as the critical spin angular velocity for rotational instability. However, in reality, the grazing collisions that have high angular momentum are likely to result in a hit-and-run, while nearly head-on collisions that have small angular momentum lead to accretion. In other words, small angular momentum collisions are selective in accretion. Thus, the accretion inefficiency may lead to slower planetary spin, compared with the perfect accretion case.

We clarify the statistical properties of terrestrial planets formed by giant impacts among protoplanets under a realistic accretion condition[5]. We derive an accretion condition for protoplanet collisions in terms of collision parameters, masses of colliding protoplanets and impact velocity and angle, by performing collision experiments with an SPH method. We implement the realistic accretion condition in *N*-body simulations and probe its effect to further generalize the model of terrestrial planet formation. We derive the statistical dynamical properties of terrestrial planets from results of a number of *N*-body simulations and compare the results with those in [6] and [4] where perfect accretion is adopted.

For the standard protoplanet system, the statistical properties of the planets obtained are the following. About half of collisions in the realistic accretion model do not lead to accretion. However, this accretion inefficiency barely lengthens the growth timescale of planets. The numbers of planets and Earth-sized planets are $\langle n \rangle \simeq 3$–$4$ and $\langle n_M \rangle \simeq 2$, respectively. The growth timescale is about 6–7×10^7 years. The masses of the largest and second-largest planets are $\langle M_1 \rangle \simeq 1.2\,M_\oplus$ and $\langle M_2 \rangle \simeq 0.7\,M_\oplus$. The largest planets tend to form around $\langle a_1 \rangle \simeq 0.8\,\mathrm{AU}$, while a_2 is widely scattered in the initial protoplanet region. Their eccentricities and inclinations are $\simeq 0.1$. These results are independent of the accretion model. The RMS spin angular velocity for the realistic accretion model is about 30% smaller than that for the perfect accretion model that is as large as the critical spin angular velocity for rotational instability (Fig. 1). The spin angular velocity and obliquity of planets obey Gaussian and isotropic distributions, respectively, independently of the accretion model.

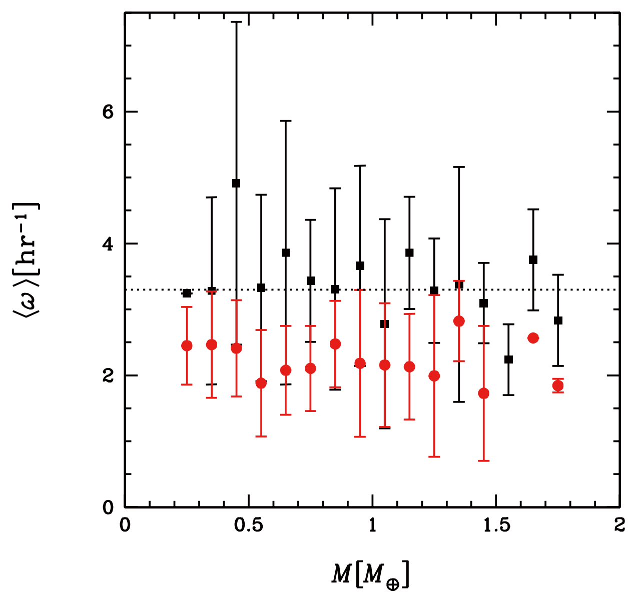

Figure 1: Average spin angular velocity of all planets formed in the 50 runs of the realistic (circle) and perfect (square) accretion models is plotted against their mass M with mass bin of $0.1\,M_\oplus$. The error bars indicate 1-σ and the dotted line shows ω_{cr}. [5]

References

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