PENTACLE: Parallelized Particle-particle Particle-tree Code for Planet Formation

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Terrestrial planets (Earth and Venus), solid core of gas planets (Jupiter and Saturn) and ice planets (Uranus and Neptune) form through collisions and coagulation between planetesimals (km-sized rocky and icy clumps). The accumulation process of planets is controlled by gravitational interactions between the celestial bodies. According to previous studies, planetary accretion has a two-staged growth mode [1,2]: (i) "runaway growth stage" in which planetesimals grow rapidly and (ii) "oligarchic growth stage" in which larger planetesimals, the so-called protoplanets, continue to slowly grow at orbital separations of several Hill radii. Today, the theoretical framework of these planetary growth process is widely accepted for the standard formation scenario of not only the solar system but also extrasolar planetary systems discovered in recent years. However, past studies on planet formation assumed "extremely large planetesimals" (about 1 / 10th of the planet size) and planetary embryos at the initial state because of the limited number of particles used in *N*-body calculations. According to previous studies on time evolution of the size distribution in a swarm of planetesimals, a typical size of a planetesimal is 1–10 km in radius, which are two orders of magnitude larger than ones assumed in previous studies and observed asteroids such as Itokawa with ~1 km in diameter. In fact, planetary accretion in a swarm of small planetesimals can may not follow the conventional oligarchic growth (e.g. [3]). Thus, it is necessary to develop a new approach that can handle such small planetesimals, namely, at least 100 million of particles in *N*-body simulations for planet formation.

In this research [4], we have newly developed a large scale *N*-body simulation code for planet formation. This code is named PENTACLE, it is freely available on GitHub. In the past planetary *N*-body simulations, it was difficult to calculate such that the number of particles exceeds 100 thousand due to limitation of calculation speed. In the *N*-body calculation, the cost of gravity computation of $O(N^2)$ per time integral of particle motion occurs (100,000 gravity calculations / 1 step for 10,000 particles). In a collisionless system which close encounters of particles do not occur, e.g., a large-scale structure of the universe, *N*-body calculations using about 2 trillion particles have been done [5]. This is because the computation cost is kept to $O(N \log N)$ by the tree method which calculates efficiently gravity forces from distant particles and the number of steps required for time integration of particle motion can be reduced. On the other hand, in the "collisional system" where close encounters of particles happen, e.g., star cluster and planetary system, dynamical evolution of the system should be calculated using short time steps (enormous number of steps). Therefore, about 100,000 particles in the collisional system are the limits of the number of particles that can be computed.

Figure 1 shows the computation time per step when *N*-body simulations of terrestrial planet formation using 1 million particles is executed with PENTACLE. The horizontal axis shows the number of cores used for the calculations, which scales to about 1000 cores. As the number of cores increases, the load of data communication limits the computation speed. We will optimize this part and aim to utilize a larger number of cores in the future. Figure 2 shows the time evolution of the energy error when changing the parameters that determine the calculation speed and accuracy. It turns out that *N*-body simulations using PENTACLE can sufficiently suppress energy errors by adopting appropriate parameters.

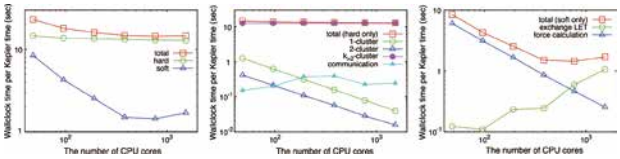

Figure 1: The calculation time per Kepler time against the number of CPU cores.

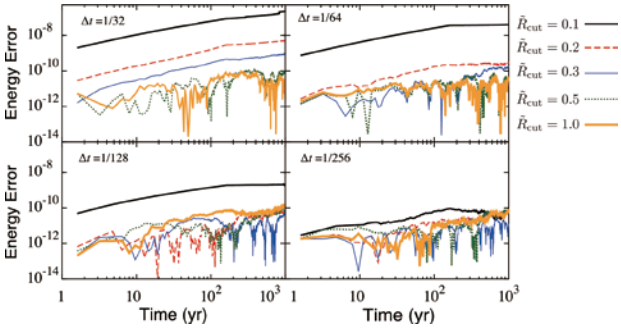

Figure 2: Relative energy error as a function of time.

References

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[5] Ishiyama, T., Nitadori, K., Makino, J.: 2012, SC12.