New initial conditions for terrestrial planet formation derived from high resolution simulations of planetesimal accretion

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Abstract

The solar system's terrestrial planets are thought to have accreted over millions of years out of a sea of smaller embryos and planetesimals. Because it is impossible to know the surface density profile for solids and size frequency distribution in the primordial solar nebula, distinguishing between the various proposed evolutionary schemes has historically been difficult. Nearly all previous simulations of terrestrial planet formation assume that Moon- to Mars-sized embryos formed throughout the inner solar system during the primordial gas-disk phase. However, validating this assumption through models of embryo accretion is computationally challenging because of the large number of bodies required. Here, we reevaluate this problem with GPU-accelerated, direct N-body simulations of embryo growth starting from \( n = 100 \) km planetesimals. We find that embryos emerging from the primordial gas phase at a given radial distance already have masses similar to the largest objects at the same semimajor axis in the modern solar system. Thus, Earth and Venus attain \( \sim 50\% \) of their modern mass, Mars-sized embryos form in the Mars region, and Ceres-massed objects are prevalent throughout the asteroid belt. Consistent with other recent work, our new initial conditions for terrestrial accretion models produce markedly improved solar system analogs when evolved through the giant impact phase of planet formation. However, we still conclude that an additional dynamical mechanism such as giant planet migration is required to prevent Earth-sized Mars analogs from growing.

GENGA: a GPU accelerated N-body package

- GENGA: parallelized version of Mercury's hybrid integrator (Grimm et al., 2014; available at https://hpc.carnegiescience.edu/hpc/resources/genga-arc)
- We use a multi-analyst approach (above) and combine and interpolate between different radial annuli of \( \sim 50000 \), fully-interacting, \( \sim 100 \) km planetesimals until the full terrestrial disk is assembled in one simulation with \( \sim 450000 \) particles.
- Our project took almost 2 years on Kepler K20 GPUs to follow the terrestrial disk through the gas disk phase for 5 Myr.

Runaway growth is highly efficient in the inner disk

Comparison with previous works: embryo mass distributions

- Considering differences in assumptions, our results of a highly evolved inner disk and unprecedented primordial asteroid belt after nebular gas dispersal are broadly consistent with other recent high-resolution studies:
  - Walsh & Levison 2019 (LIPAD)
  - Carter et al. 2015 (PKDGRAV)
- We assess that the minor differences are mainly due to the different initial SFDs of planetesimals assumed in each study.
- The major conclusion of these different high-resolution investigations is that the giant impact phase unfolds as a “delayed instability” between a small population (10-15) of large proto-planets (1-5 times Mars’ mass).
- The last giant impact on Earth often involves equal-mass objects (e.g. Camp2012).
- The innermost regions of the disk are highly depleted of planetesimals as runaway growth proceeds outward like a wave.
- We find that future studies attempting to follow a similar interpolation scheme should interpolate logarithmically between annuli, rather than linearly.

Comparison with previous works: Size Frequency Distributions (SFDs)

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References