# Formation of terrestrial planets from protoplanets in a dissipating protoplanetary disk

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We calculated the collisional evolution of terrestrial planets from protoplanets including the effect of protoplanetary gas disk's depletion.

Following oligarchic growth, the protoplanets will have masses comparable to Mars and be separated by approximately 10 Hill radii. The orbits of these isolated protoplanets become unstable through long term gravitational interaction. The protoplanet grows up to it's final size trough giant impacts, but the formed systems become eccentric as a result [1]. Although mechanisms which damp the eccentricity have been proposed, such as the dynamical friction in the planetesimal disk [2] and the tidal interaction between the gas disk and protoplanet [3, 4, 5, 6], these mechanisms also prevent orbit crossing and planetary growth [7,8], and require fine tuning the relation between formation of the planets and dissipation of the disk [9,10].

This dilemma can be solved if the protoplanetary collisions occur in an environment where the damping is still working. To achieve this, we consider the sweeping secular resonance. After the formation of the Jovian planets, the gas disk starts to deplete. The depletion changes the gravitational potential and causes the sweeping of the secular resonance. The resonance excites the eccentricities of isolated protoplanets and leads to the orbit crossing. Because the remnant disk is still present, the gas drag due to the tidal interaction is still effective.

We put 30-40 isolation mass protoplanets from 0.5 to 4 AU, Jupiter and Saturn (with present-day orbital elements) initially. We assumed exponential decay of the gas of the minimum mass disk whose e-folding time is 1Myr-10Myr.

The results of numerical simulation are rapid final accretion and small eccentricities of terrestrial planets. Our simulations normally end up with 3-7 circular planets inside 2AU. We found that the forced eccentricity near the secular resonance induces the migration of protoplanets; the protoplanet falls in advance of resonance. With the migration and pumping up of the eccentricity, the protoplanets beyond 2AU become unstable within 1 Myr after the formation of Jupiter, and they merged to 3-5 large protoplanets. As the secular resonance sweeps in, these large protoplanets migrate in, accreting the other protoplanets. After about 10 Myrs, the resonance comes in the inner part of terrestrial region, and the inner protoplanets start to grow. The gas density decreases to a few percent of minimum mass disk by this stage. While the tidal drag still works, the tidal damping timescale becomes longer than the migration timescale of the secular resonance, the secular resonance capture is solved. The resonance passes leaving behind several grown-up terrestrial planets. The resonance does not reach less than 0.6AU. The eccentricities of the protoplanets in this region cannot be excited for a long time, and their final accretion would be done through the long-term instability. This may be a reason of a large eccentricity of Mercury.

We will also discuss about the water delivery to the Earth. Small planetesimals in the asteroid belt can acquire and retain water. Although the critical size of water rich planetesimals and their degree of hydration evolve with time, the combine effect of sweeping secular resonance and gas drag can drive wet asteroids to the inner solar system. Taking into account the decay of 26Al the retention capability of the large protoplanet, we estimate the water content of the emerging terrestrial planets.

Reference

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