Oligarchic Growth of Protoplanets

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We have investigated late stage of planetary accretion using 3-D N-body simulations. We found that in late stage a group of protoplanets (runaway planetesimals or embryos) with similar masses grows oligarchically, while most planetesimals remain small. We also found that the protoplanets are on nearly circular orbits and their separations are roughly constant. Their typical orbital separation is $\sim 10r_{\rm H}$, where $r_{\rm H}$ is the Hill radius defined by $r_{\rm H} = (M/3M_{\odot})^{1/3}a$ where M and a are the mass and the semimajor axis of a protoplanet and $M_{\odot}$ is the solar mass.

The formation of the protoplanets with similar masses and equal spacings in the Hill radius is explained as follows. Energy equipartition due to dynamical friction makes orbits of large bodies nearly circular, which causes runaway growth[1]. As runaway growth proceeds, the growth of the runaway planetesimal slows down[2]. This self-limiting nature is caused by the increase of the velocity dispersion of neighbor planetesimals due to gravitational scattering by the runaway body. Then, the runaway growth of the most massive body halted and the less massive runaway bodies grow more rapidly and become comparable to the most massive body. Thus, protoplanets with similar masses are formed. As they grow, the orbital repulsion between them rearranges them with orbital separations $> 5r_{\rm H}$[3]. The orbital repulsion is caused by the coupling of scattering between protoplanets and dynamical friction by small planetesimals. The orbital separation of two protoplanets increases keeping orbits nearly circular. This process continues until the separation becomes larger than $5r_{\rm H}$. As protoplanets grow, their orbital separations measured by their Hill radii become small, since $r_{\rm H} \propto M^{1/3}$. This implies that they repeat the orbital repulsion while growing. It is noted that for such distance protoplanets hardly collide with one another and hence they grow accreting small planetesimals rather than colliding with one another. Consequently, a group of protoplanets with orbital separations $\sim 10r_{\rm H}$ is formed. We will comment that this result can explain the present arrangment of Jovian planets.

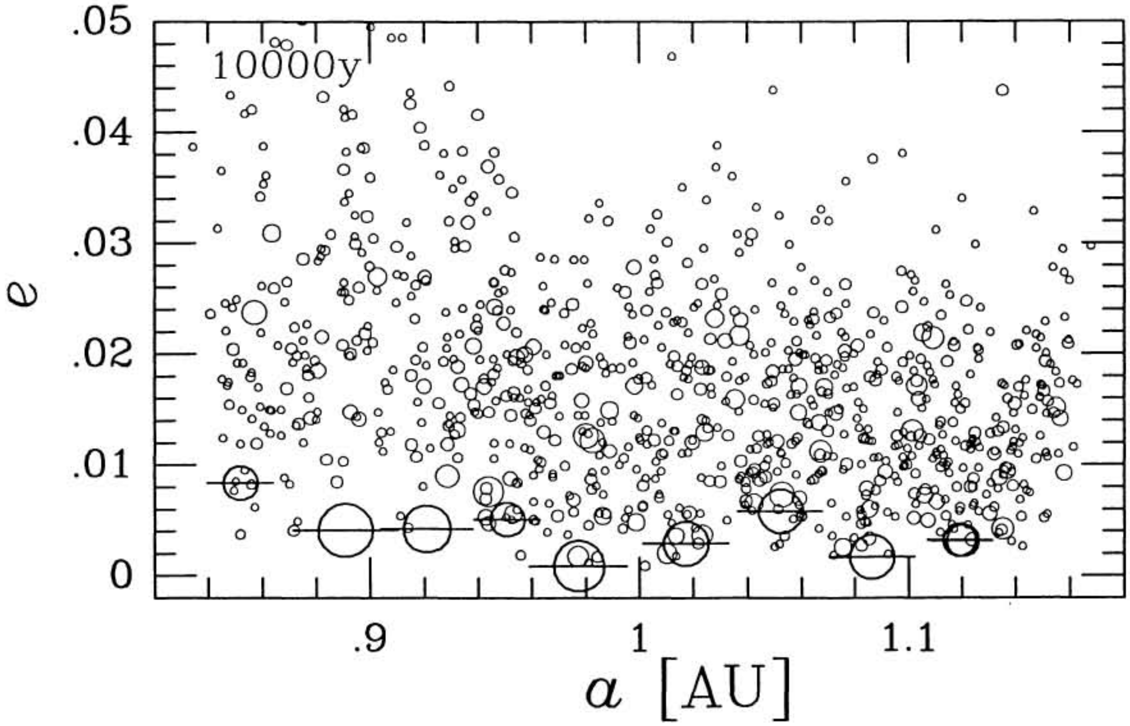

Figure 1: The snapshot of the planetesimal system on the a-e plane at $t = 10000$y, where a and e are the semimajor axis and the eccentricity of planetesimals. The circles represent planetesimals and their radii are proportional to the radii of planetesimals. The system initially consists of 4000 equal-mass (10^{24}g) planetesimals in a ring-like region around $a = 1$AU. The surface mass density is $10\mathrm{gcm}^{-2}$. We accelerate the accretion process by using 10-fold radii of planetesimals. We assume that two planetesimals always accrete when they contact. The numbers of planetesimals is 882 at $t = 10000$y. We draw lines with the length of $5r_{\mathrm{H}}$ from the center of protoplanets to both sides. The protoplanets are selected if their masses are larger than 1/5 of the maximum mass. Their masses are of order 10^{26}g and their orbital separations are all $\sim 10r_{\mathrm{H}}$.

References

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