
A calculation has been made of the mass and velocity evolution of a planetesimal swarm up to the stage at which \(-10^{26}\) g planetary "embryos" are formed. The initial swarm contains 8.33 x \(10^8\) bodies of 7.3 km radius in an annulus 0.17 AU in width, centered at 1 AU. The total mass of the swarm is \(4 \times 10^{27}\) g. The method of calculation is an extension of the "gas dynamics" model described earlier (1,2). As before, the continuous mass distribution is approximated by a series of batches of bodies that grow in mass by collisions with one another. Their velocities are changed by mutual gravitational perturbations, collisions, and gas drag. The present calculations differ from those reported earlier in that:

1. The results of Ida (3) and Greenzweig and Lissauer (4) are used to calculate gravitational perturbations and collision rates when relative velocities are less than 2 Hill units.
2. New expressions for velocity perturbations permit separate calculation of eccentricity and inclination changes.
3. The radial extent of the swarm is larger than the "gravitational range" of the largest bodies, resulting in absence of close encounters between these largest bodies.
4. The effects of fragmentation (both catastrophic and cratering) cause the formation of a fragmentation distribution assumed to extend down to bodies 1 meter in radius.
5. Mass is lost from the system by gas drag.

These more complete results confirm and extend those reported earlier (2). It is found that within 12000 years, energy equipartition lowers the velocities of the larger bodies sufficiently to initiate a discontinuous runaway growth of about 30 bodies in nearly circular coplanar orbits, in total containing at first only \(-3\%\) of the swarm's mass. Beyond this time, the mass distribution becomes trimodal:

1. The very low velocity runaway group that continues to grow by sweep up of smaller bodies and by rare collisions with one another. These bodies become "embryos" of mass \(-10^{26}\) g in \(-45000\) years.
2. A residual swarm of partially grown 10-200 km diameter bodies that essentially stops growing, and loses mass to sweep up by runaway bodies and by destructive mutual collisions at \(-300\) m/sec.
3. A lower velocity fragmentation tail, the smaller size portion of which comprises an approximately steady state collision cascade, balanced between input of fragments of larger bodies, and loss by sweep up by runaways and gas drag loss to smaller heliocentric distances.

The thermal evolution of these growing embryos is relevant to understanding the state of differentiation of the objects that participated in the giant impacts that characterized the final
stage of terrestrial planet growth. It is also possible that fragments of such embryos, originally both in the terrestrial planet region and the asteroid belt, are ancestral to present day differentiated asteroids and igneous and metamorphic meteorites.

There are three primary contributors to the thermal energy of the accreting embryo: 1) radiogenic heating, dominated by $^{26}\text{Al}$; 2) small impacts, defined here as any impact with projectile mass less than $10^{24}\text{g}$; and 3) large impacts. At a heliocentric distance of 1 AU, the largest embryo has grown to a mass of about $10^{26}\text{g}$ in 45,000 years. Over this time period, heating due to decay of $^{26}\text{Al}$ can result in a temperature rise of only 50-200 K at the center of the body. This effect will be more important at later times. Small impacts contribute most of the mass and energy to the embryo, but the temperature rise is concentrated near the surface, and impact stirring and radiation to space result in the loss of much of this energy. The small impacts may result in a temperature of 500 to 1000 K in the outer portion of the largest embryo towards the end of this period.

The velocity of large impacts ($>10^{24}\text{g}$) is essentially the mutual escape velocity (1 to 3 km/s). The largest embryo at the end of this time has experienced 5 to 10 such large impacts. The effects of these very large impacts at only moderately high velocities are not well understood. Based on available calculations (5,6) some estimates can be made. These impacts probably have two principal effects. Local heating takes place in a hemisphere centered on the impact with a volume approximately equal to that of the impactor. In this region temperatures rise 100 to 600 K, depending on the impact velocity and obliquity. The other effect of a large impact is embryo-wide shock heating, which can raise central temperatures by 50 to 300 K, depending on velocity, obliquity and size of impactor. Because the time scales are too short for conduction to be important, the temperature changes in the interior are essentially additive (unless melting occurs) and the central temperature over the period studied can rise to 1000 - 1500 K. Thus it can be expected that global metamorphism will result, and possibly partial melting as well.

REFERENCES