Accumulation of the Planets

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A. Early Stages of Planetary Growth.

In modelling the accumulation of planetesimals into planets, it is appropriate to distinguish between two stages:

(A) An early stage, during which ~ 10 km diameter planetesimals accumulate locally to form bodies ~ 10^{25} g in mass. During this stage, it is useful to treat the bodies as particles, analogous to gas molecules in the kinetic theory of gases.

(B) A later stage in which the ~ 10^{25} g planetesimals accumulate into the final planets. During this stage it is likely that bodies will become well-mixed as a consequence of radial excursions and the "giant" impacts will occur. During this stage it is better to trace the orbital evolution of the larger individual bodies.

Previous work on the early stage has been extended by use of new expressions developed by G. R. Stewart of the University of Virginia to describe the changes in velocity of the bodies as a consequence of mutual gravitational perturbations, collisions, and gas drag. The contribution of one of these terms, "dynamical friction", has not been included in any earlier calculations, and all previous workers have neglected at least one of the other terms as well.

In the terrestrial planet region, an initial planetesimal swarm corresponding to the critical mass of dust layer gravitational instabilities is considered. It is assumed these bodies have an initial exponential mass distribution $dN \alpha e^{-m/m_o} dm$ where $m_o = 3 \times 10^{18}$ (11.5 km diameter) and an initial relative velocity of 11 m/sec, and the gas density to be 1.18×10^{-9} g/cm^3. The continuous distribution is modelled as an assemblage of 10^8 bodies divided into 22 "batches", each batch containing bodies of equal mass distributed over a zone of width $\Delta a = 0.02$ A.U. The size and velocity evolution of each batch is followed through successive time steps by calculating the effects of gravitational perturbations, collisions, gas drag, merger, and fragmentation. When appropriate, the effect of low velocities on the gravitational cross-section was included.

For a continuous initial size distribution, as assumed by previous workers, an orderly growth is found, the early stage of accumulation ending when most of the mass of the terrestrial planet region is concentrated in ~3000 bodies ranging from ~ 10^{24} g to ~ 10^{25} grams in mass at the time (~ 10^6 years) that eccentricities rose to ~.01.

"Runaway accretion", in which most of the mass of the zone becomes concentrated in a single low eccentricity $\geq 10^{26}$ g body in $< 10^5$ years, was found to require a discontinuous initial mass distribution, i.e. a "seed" at the upper end of the distribution. The size of the seed required is somewhat dependent on the parameters assumed for gas drag and fragmentation. For the more plausible values, a "seed" 2 to 3 times the mass of the 2nd largest body is required. The presence or absence of such seeds is not at present predictable. For this reason, it is permissible to speculatively entertain models in which volatile-rich seeds are formed beyond the "snow line" of the solar nebula at ~5 A.U., but not in the asteroid belt and the terrestrial planet region. This could be a factor in facilitating the rapid growth of planetesimals of Jupiter and Saturn, despite the relatively long accumulation times conventionally associated with these large heliocentric distances.

B. Late Stages of Planetary Growth.

Our previous work on this problem has concentrated on the larger terrestrial planets, Earth and Venus. Because of their smaller size and less "averaging", the present state and chemical composition of Mercury and Mars may be expected to be more diagnostic of events during planet formation.

In order to understand better the accumulation history of Mercury-size bodies, 19 new Monte-Carlo simulations of terrestrial planet growth have been calculated. Three cases are presented, involving different assumptions regarding the initial state of the final stage of planetary accumulation and the degree and ease with which planets can be collisionally disrupted. It is found that the same conditions that lead to Mars-size giant impacts on Earth and Venus imply a more catastrophic fragmentation history for Mercury-size bodies and the fragments from which they accumulated. In accordance with these results, it may be speculated that the large iron core of Mercury may be a consequence of a giant impact that removed the silicate mantle from a previously differentiated body. Less extreme fragmentation events may also contribute to chemical fractionation processes for which bodies in this mass range may be especially susceptible. It is also found that planets of the size and position of Mercury will accumulate material originating over the entire terrestrial planet range of heliocentric distances. This tends to reduce the relative importance of more primordial chemical fractionation processes.

C. Primitive Earth-approaching Bodies (Meteorites, Apollo-Amors, Meteors).

A Monte Carlo technique has been used to investigate the orbital evolution of asteroidal collision debris produced interior to 2.6 A.U. It is found that there are two regions primarily responsible for production of Earth-crossing meteoritic material and Apollo objects. The region adjacent to the 3:1 Jovian commensurability resonance (2.5 A.U.) is unique in providing material in the required quantity and orbital distribution of the ordinary chondrites. This region should also supply a comparable preatmospheric flux of carbonaceous meteorites. This work has been extended to include the innermost asteroid belt. The innermost asteroid belt (2.17 to 2.25 A.U.), via the v_6 secular resonance, provides a flux ~9% that of the ordinary chondrites, and appears to be the strongest candidate for the basaltic achondrite source region. It is unlikely that a significant number of meteorites originate beyond 2.6 A.U. It is speculated that enstatite achondrites are derived from the Hungaria region, interior to the main belt, and that iron and stony-iron meteorites originate from many main belt sources interior to 2.6 A.U.

The same techniques have been extended to include the origin of Earth-approaching asteroidal bodies. It is found that these same two resonant mechanisms predict a steady-state number of Apollo-Amor about 1/2 that estimated based on astronomical observations. There are some types of observed Apollo-Amor orbits that are observationally overpopulated by a factor of 10 - 30 when compared with predictions of the asteroidal source model. These deficiencies are remedied by postulation of additional production of Apollo-Amor objects as outgassed comets at a rate of $\sim 10^{-5}$ yr^{-1}.

Particularly puzzling questions are raised by sun-approaching bodies, and attention is being given to these. Two Apollo objects have perihelia <0.2 A.U. and aphelia <2.5 A.U. (1566 Icarus and 1983TB). The latter is associated with the Geminids, the second most prolific of the annual meteor showers. At least 1% of the Prairie Network fireballs are in similarly small orbits; because of selective effects the fraction must be higher (e.g. Geminids were excluded in reducing the data). These orbits are unstable on a time scale of $\sim 10^7$ years and a fairly productive source is required. None of the known mechanisms (either cometary or asteroidal) for supplying Earth-crossing material can accomplish this.

This lack of correspondence with known cometary and asteroidal material has been extended by examination of the atmospheric trajectories of six -5 to -8 magnitude meteors: three bright Geminids reported by Jacchia and three non-Geminid Prairie Network fireballs in similar Sun-approaching orbits. These objects, both Geminid and non-Geminid, also show physical similarities to one another. All of them are Ceplecha and McCrosky type I fireballs, in this way we have identified as ordinary chondrites. Their ratio of photometric/dynamic mass is at least as small, and often smaller than ordinary chondritic fireballs, a further indication of strong, dense bodies. They are clearly unlike typical Taurids (Comet Encke) and other cometary fireballs which fragment more easily and are probably of lower density.

These bodies, however, have much lower ablation coefficients ($\sigma \sim 5 \times 10^{-13}$ sec^2/cm^2) than ordinary chondritic asteroidal fireballs ($\sigma \sim 2 \times 10^{-12}$ sec^2/cm^2). If loss by ablation were all that mattered, a Geminid would retain 4% of its initial mass while penetrating the atmosphere, despite its entry velocity of 36 km/sec. Nevertheless, they fail to fully decelerate in the atmosphere, instead they disappear at velocities of 17-32 km/sec at dynamic pressures of $\sim 10^7$ dynes/cm^2. For this reason, their breaking strength appears to be no greater than ordinary chondrites, despite all this other quantitative evidence for "toughness". The relatively small mass ($\sim 1 - 100$g) of these bodies makes it difficult to know whether or not any possibly collectible material survives their apparent disappearance. Measurement and reduction of larger Geminids on fireball network photographs could permit addressing this question.