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ACCRETION AND EVOLUTION OF SOLAR SYSTEM BODIES.

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We use a combination of analytical and numerical methods to study dynamical processes involved in the formation of planets and smaller bodies in the solar system. Our goal is to identify and understand critical processes and to link them in a numerical model of planetesimal accretion. We study effects of these processes by applying them in the context of the "standard" model of solar system formation (Wetherill, 1988), which involves accretion of the terrestrial planets and cores of the giant planets from small (~km sized) planetesimals. The principal focus of our research effort is the numerical simulation of accretion of a swarm of planetesimals into bodies of planetary size. Our computer code, based on the approach of Spaute *et al.*, (1985), uses a Monte Carlo method to determine collisional interactions within the swarm. These interactions are not determined simply by a relative velocity, but rather by explicit distributions of keplerian orbital elements. The planetesimal swarm is divided into a number of zones in semimajor axis, which are allowed to interact. The present version of our code has the capability of following detailed distributions of size, eccentricity, and inclination in each zone.

The statistical method allows simulations to begin with large numbers ($\geq 10^{12}$) of planetesimals. The spatial resolution of our model avoids the inherent limitations of the "particle-in-a-box" approach, particularly the fact that the "box" becomes inhomogeneous as accretion produces a small number of large protoplanetary bodies. Our method allows explicit inclusion of such phenomena as exchange of mass between zones, spreading of the swarm due to collisions, local depletion of the planetesimal population near the orbit of a large embryo ("dynamical isolation"), distant gravitational perturbations by bodies in non-crossing orbits, and secular decay of orbits due to gas drag. Our code also can follow the evolution of discrete bodies, i.e., a small number of bodies at the large end of the size distribution can be assigned individual values of orbital elements. Their subsequent evolution is followed separately as they interact with the continuum swarm and with each other. Early-stage modeling, using particle-in-box formalism (Greenberg *et al.*, 1978; Wetherill and Stewart 1989) has not been able to follow evolution of the swarm to produce bodies of planetary mass, due to breakdown of the assumptions of the models. Methods that follow the orbital evolution of individual bodies (Wetherill 1986) are limited to a few hundred bodies, and their initial conditions can be inferred only by extrapolation of the early-stage results. Our goal is to use the unique capabilities of our code to bridge the gap between the early and final stages of planet formation.

During the past year we have added new capabilities to our computer code and have begun to use it to model more complex and realistic situations, such as accretion of planetesimals in multiple zones spanning a broad range of semimajor axes. These simulations are being extended to later stages of planetary growth, using the "discrete bodies" algorithm. We have also continued testing and verification of our code in order to ensure its accuracy.

Wetherill and Stewart (1989) pointed out that there are two possible modes of planetary growth, with qualitatively different outcomes. One is "orderly" growth, in which many of the largest bodies maintain comparable sizes as they gain in mass. The other is "runaway" growth, in which a single large body forms at the large end of the size distribution. In the complex problem of planetary accretion, it is conceivable that growth in different stages might change from one mode to the other. Thus, a numerical code must be able to handle both types of growth. Recently, Wetherill (1990) demonstrated an analytic solution for a coagulation kernel proportional to the product of the masses, a situation that results in extreme runaway growth. A test of our code in this case demonstrates excellent agreement with the analytic solution (Fig. 1).

Agreement with analytic solutions is a necessary, but not sufficient, condition for correct computation of the more complex problem of planetary accretion. Our code, when applied to a single heliocentric distance zone, produced results in good agreement with the particle-in-a-box calculations of Wetherill and Stewart (1989). During the past year we have gone beyond these simulations in order to exploit the unique features of our code--its use of discrete bodies on individual orbits, and ability to model multiple zones over a range of heliocentric distances.

Discrete Bodies: The initially numerous ($\sim 10^{12}$) small planetesimals cannot be treated as individual bodies, but must be dealt with as having continuous distributions of size and orbital elements. However, accretion eventually produces some large bodies in numbers small enough to be treated individually. Indeed, they must be treated separately, to the degree that their growth is a stochastic process involving discontinuous changes, e.g., due to mutual collisions of these large bodies. Once the planetesimal swarm has evolved to the point where there is a small number (typically <10) of bodies in the largest size bin of a given radial zone, we assign each of these bodies orbital elements (a, e, i) chosen randomly within the limits of the continuum bin. Their later evolution--mass gain by accretion from the continuum, mutual collisions, and evolution of orbits due to gravitational stirring and impacts--is computed separately for each body. With this approach, we avoid problems due to small or fractional numbers of bodies in the largest size bins, and can determine whether the first-formed body will grow to dominate its zone, or perhaps whether two smaller ones will coalesce and form a new largest body.

Multiple Zones. Figures 2 and 3 show results of calculations of the simultaneous evolution of bodies in four heliocentric distance zones. Figure 2 tracks the mass of the largest body in each zone vs. time. Due to the higher surface density and shorter orbital periods in the innermost zone, runaway growth occurs there first, with the other zones following in order. After $\sim 10^5$ years, runaway growth slows down due to increasing relative velocities (eccentricities) of the smaller bodies by gravitational stirring. Figure 3 shows results for two such simulations using different seeds for the random number generator. The criterion for creating discrete bodies was such that $\lesssim 2$ per zone were produced. The zones were broad enough, and their eccentricities low enough, that their orbits did not cross. However, the abundant smaller bodies in the swarm had higher eccentricities, and could interact with bodies in other zones. One result of this, seen in the second simulation (triangles), was that the largest body in the innermost zone "stole" enough mass from the next zone so that no discrete body formed there.

Figure 4 shows a simulation having 15 heliocentric distance zones from 0.9 to 1.1 AU. After 10^5 years of model time, stochastic effects have produced runaway growth and discrete bodies in most, but not all, zones.

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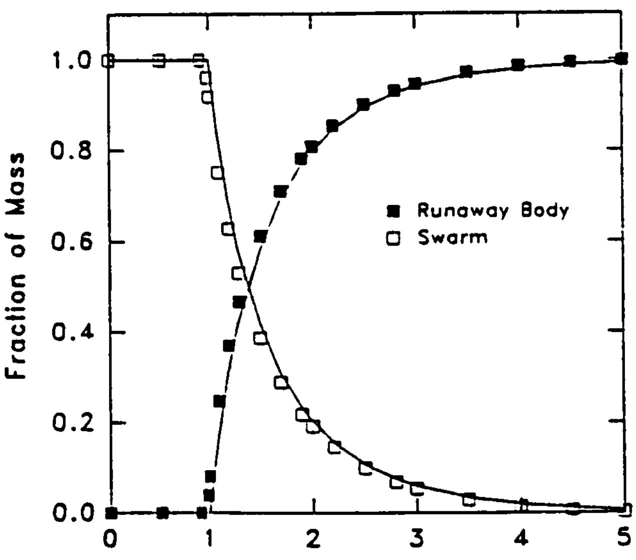

Figure 1. Results of numerical simulation of runaway growth of a large body. Solid lines are the analytic solution of Wetherill (1990a). Symbols are numerical solution for the runaway body that formed at η = 0.97.

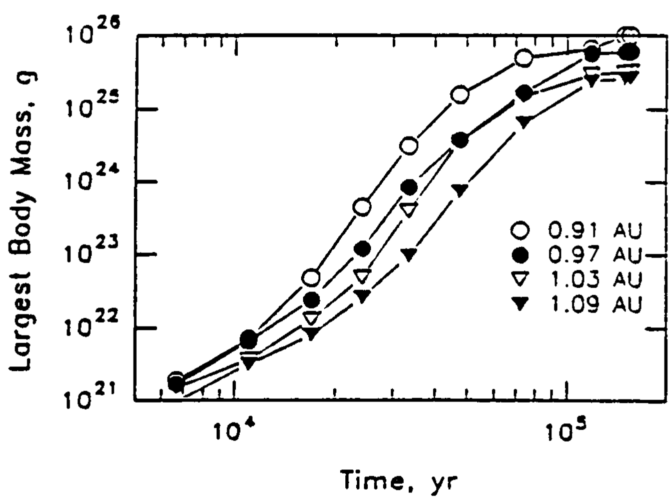

Figure 2. Growth of masses of largest bodies (continuum bins) in four heliocentric zones extending from 0.88 to 1.12 AU. Runaway growth occurs earlier at smaller heliocentric distances.

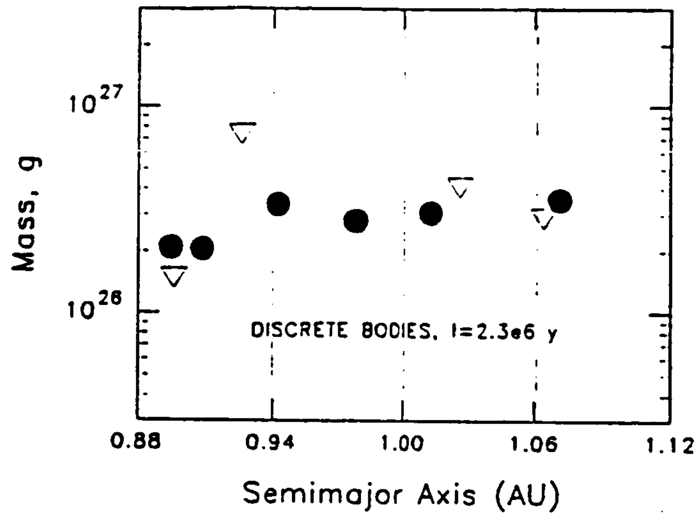

Figure 3. Outcomes of two simulations of accretion in four zones, with discrete bodies introduced at a threshold mass of 5×10^{25} g. Identical parameters were used, but with different sequences of random numbers.

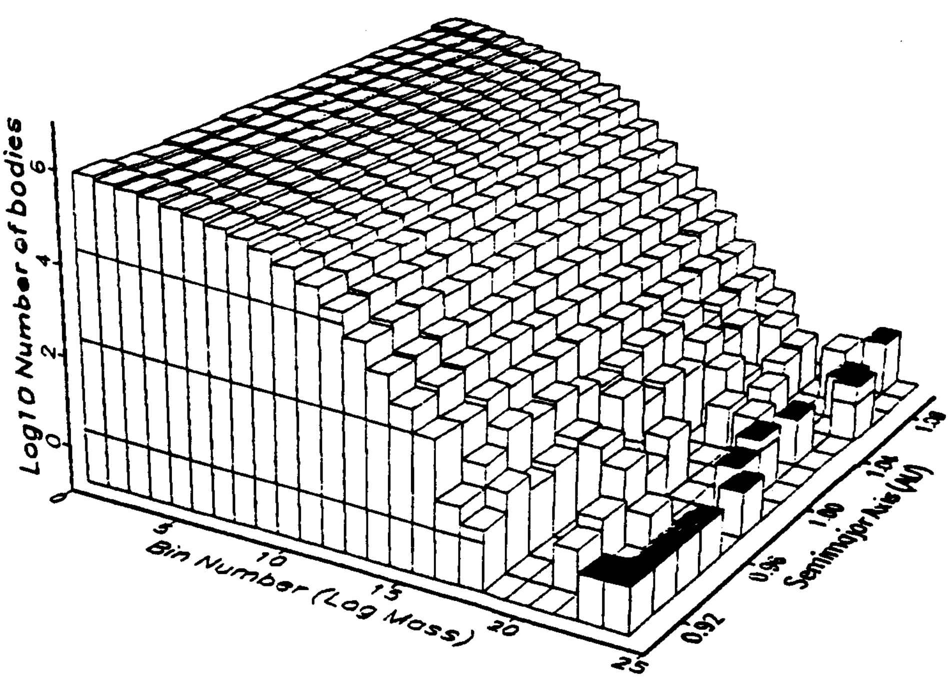

Figure 4. Size distribution of bodies in 15 heliocentric distance zones spanning a range 0.9-1.1 A.U. Initial surface density proportional to $r^{-3/2}$. Results are shown for a model time of 10^5 y. Columns with black tops represent discrete bodies.