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A REEXAMINATION OF EARLY NUMERICAL SIMULATIONS OF PLANETARY ACCRETION.

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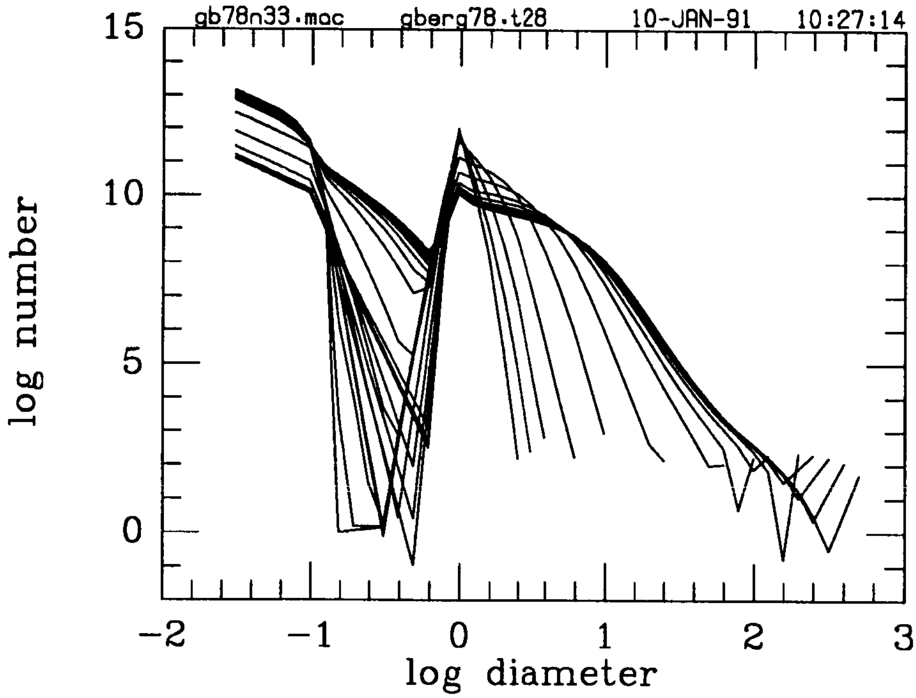
The intermediate stage of protoplanetary accretion, where sub–km sized bodies accrete in 500–1000 km diameter bodies, is critical in determining the character of subsequent evolution. Originally, Safronov (1972) posited that this accumulation occurred through "steady state" growth, where the largest bodies controlled (and stirred up) the random–velocity distribution of smaller particles. This model led to untenably long timescales for outer–planet formation. Greenberg et al. (1978) discovered that, at least through the formation of 500 km planetary embryos, the small particles dominate the population and control the velocity distribution, keeping velocities much smaller and setting up the possibility of "runaway accretion", where the largest body is able to accumulate quickly a much greater mass and separate itself from the continuum of the size distribution. This perspective has since been adopted by the majority of workers in the field. However, some controversy remains as to the exact methods used by Greenberg et al. (1978). I have reviewed that planet formation model in detail to address these criticisms and better explain the algorithms used in the study. In particular, the algorithms for mutual velocity stirring among planetesimals and mass shifting between adjacent diameter bins are rederived in detail. I have also examined the likelihood of artificial acceleration of the runaway growth phase of the intermediate stage of planetesimal formation.

A great deal of criticism has been leveled at the velocity stirring algorithm used by Greenberg et al. (cf. Wetherill 1990). In the 1978 paper, the velocity equations shown were approximations, given to demonstrate some of the salient features of velocity evolution; they were not the exact algorithms used in the numerical simulation. Upon reviewing the original algorithm and subsequent improvements (cf. Greenberg 1982 and Greenberg et al. 1984), I find that all relevant physical effects included in recent models by various authors were accounted for in the earlier work, including dynamical friction and the stirring due to random velocities to approximately the same accuracy as current models. A detailed exposition of this algorithm is beyond the scope of this abstract, but a more thorough examination is in preparation (Kolvoord and Greenberg 1991). While the exact form of the random velocity stirring algorithm was occasionally modified and experimentally improved (*e.g.*, between 1978 and 1982) from the original work of Greenberg et al. (1978) [Greenberg 1982 uses the improved form], dynamical friction (cited by Wetherill and Stewart (1989) as a key effect) was included from the outset, as part of accounting for rotation of the appropriate velocity vectors during gravitational encounters.

Much comment has also been made about the possibility of artificial acceleration of growth in the Greenberg et al. models (cf. Wetherill and Stewart 1989, Ohtsuki et al. 1990). It should be noted that this possibility was recognized by the authors and discussed in Greenberg (1982). While some artificial acceleration is caused by the coarseness of the mass-binning algorithm, it is small (approximately a factor of 2), and given the other uncertainties in the problem it has a limited effect. The figure below shows a new simulation using the Greenberg model with a smaller bin size (each bin is separated by a factor of 2 in mass rather than in diameter) and nominal values for the various strength parameters. I find that it takes on the order of 50,000 years to form a 500 km body, in agreement with other findings in the current literature. The result of Greenberg et al. (1978) was of this same order of magnitude, i. e. reasonably accurate compared with various recent studies, and distinct from the Safronov paradigm which was current at that time.

In summary, our review and tests indicate that the model and conclusions of Greenberg et al. (1978), with the revisions as given in Greenberg (1982), are robust. The velocity stirring algorithms include all of the applicable physics and the artificial acceleration caused by too broad mass bins is a relatively minor effect.



A plot of the evolution of number versus size for a model initially populated by 1 km bodies. The parameters in the model are the same as those used in Greenberg, except for the bin size which is now a factor of 2 in mass.

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