DYNAMICAL STABILITY OF SYSTEMS OF PLANETARY EMBRYOS. J. E. Chambers, G. W. Wetherill, and A. P. Boss, DTM, Carnegie Institution of Washington, 5241 Broad Branch Road N.W., Washington DC 20015-1305.

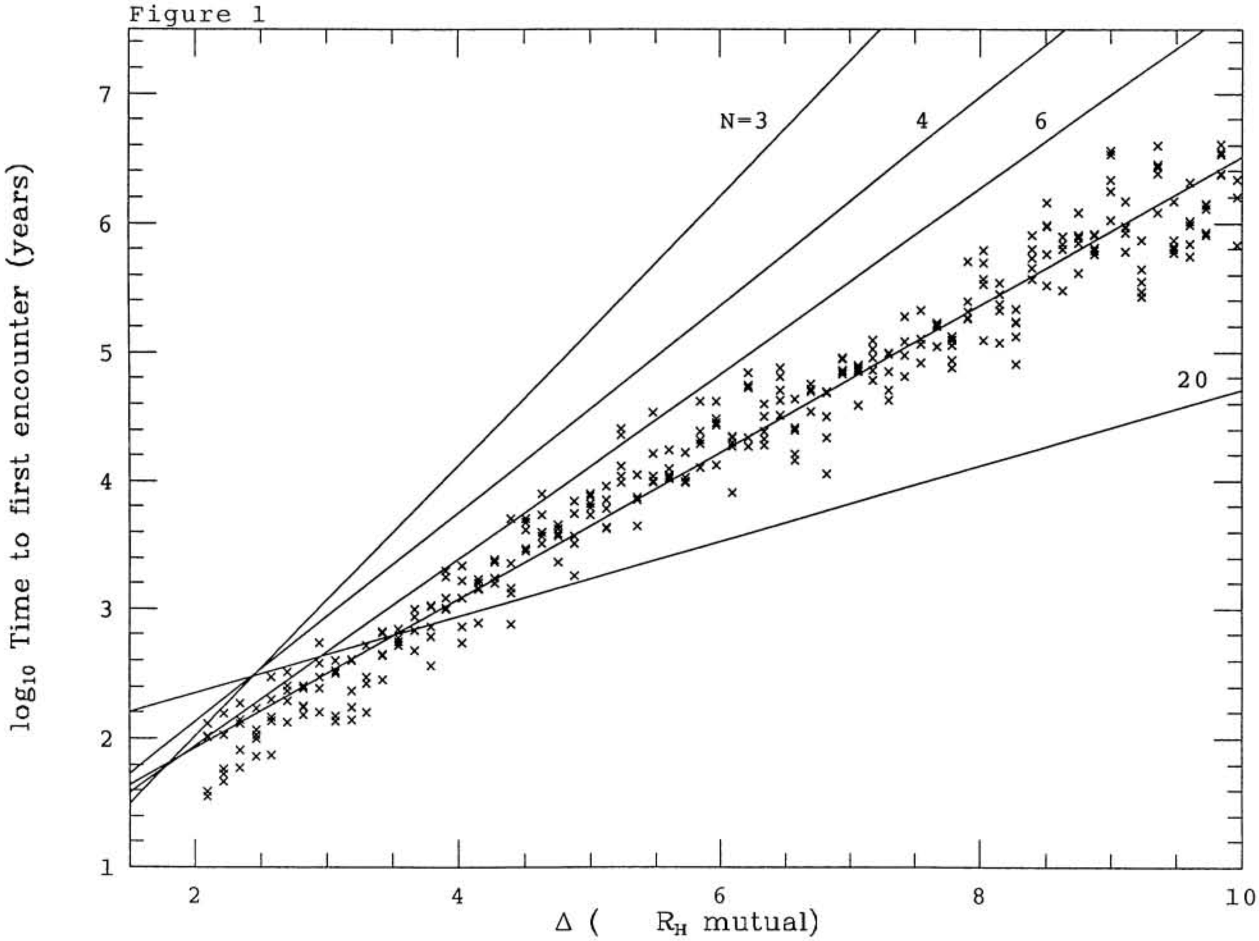
Recent work on the early stages of the formation of the inner planetary system predicts the creation, via runaway growth, of a large number of lunar-to-Mercury-sized embryos constrained to move on nearly circular coplanar orbits by dynamical friction with residual small bodies [1-4]. It is not well understood how this system evolves into one in which close encounters between embryos can occur allowing them to coalesce into final planets. Gladman [5] has shown that systems of two embryos generally avoid close encounters indefinitely if their initial orbital separation Δ exceeds a critical value. We extend this work to systems of up to 20 embryos. In general, these systems are unstable with respect to close encounters, with the time t to first encounter roughly increasing as $t \propto \exp(\Delta/\Delta_0)$, where Δ_0 is a constant. Thus multi-embryo systems are much less stable with respect to close encounters than the two-embryo case.

These conclusions are based upon a large number of numerical integrations of systems of N planetary embryos of mass $10^{-7} M_\odot$ on initially circular, coplanar orbits. For each value of N, five sets of initial embryo longitudes were chosen at random, so that the longitude difference between adjacent embryos was at least 20°. For each set of initial longitudes we ran integrations for many values of Δ, such that the initial orbital semi-major axes are a_0, $a_0 + \Delta$, $a_0 + 2\Delta$ etc., where a_0 is a constant. The integrations were performed using Levison & Duncan's second-order symplectic integrator [6,7] using a range of step sizes, terminating each integration whenever a pair of embryos approached one another by less than one Hill radius. The results do not appear to depend upon the integrator step size used or the particular set of initial longitudes of the embryos.

In a typical integration the orbital eccentricities of the embryos exhibit high frequency oscillations, whose magnitude slowly increases with time. Towards the end of the integration the oscillations grow more rapidly, until the orbits of adjacent embryos approach one another and close encounters can occur. At this stage significant energy exchange between embryos takes place, and their semi-major axes begin to vary, increasing the likelihood of further close encounters. From this point on we would expect the evolution to proceed very rapidly as all the embryos suddenly become able to undergo encounters and/or collisions with one another.

Figure 1 shows the time t of first close encounter versus Δ for a large number of runs involving 10 embryos. Note the approximately linear dependence of $\log t$ on Δ. This linear dependence is also found for $10^{-5} M_\odot$ mass embryos, and for other values of N, with the slope varying in each case as indicated by the other lines in Figure 1 corresponding to $N = 3$, 4, 6 and 20. Thus, as the number of gravitating bodies increases, the lifetime of the system to first close encounter becomes less dependent upon Δ.

Figure 1



REFERENCES.

[1] Wetherill, G. W., & Stewart, G. (1989). Accumulation of a swarm of small planetesimals, *Icarus*, **77**, 330.

[2] Wetherill, G. W., & Stewart, G. (1993). Formation of planetary embryos: Effects of fragmentation, low-velocity and independent variation of eccentricity and inclination, *Icarus*, **106**, 190.

[3] Kokubo, E., & Ida, S. (1995). Orbital evolution of protoplanets embedded in a swarm of planetesimals, *Icarus*, in press.

[4] Lissauer, J. J., & Stewart, G. R. (1993). Growth of planets from planetesimals, in *Protostars and Planets III*, eds. E. H. Levy & J. I. Lunine (Tucson: Univ. Arizona), 1061.

[5] Gladman, B. (1993). Dynamics of systems of two close planets, *Icarus*, **106**, 247.

[6] Levison, H. F., & Duncan, M. J. (1994). The long-term dynamical behaviour of short-period comets, *Icarus*, **108**, 18.

[7] Wisdom, J., & Holman, M. (1991). Symplectic maps for the N-body problem, *Astron. J.*, **102**, 1528.