OUTCOMES OF GRAVITATIONAL ENCOUNTERS OF A PLANETESIMAL WITH A PLANETARY EMBRYO; A. Carusi*, R. Greenberg**, and G.B. Valsecchi*
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Gravitational encounters influenced the process of planet formation by controlling the relative velocities among the small bodies of the early solar system and by determining collision probabilities. Most models (e.g. 1,2) assume that encounters can be approximated by a two-body interaction, which temporarily neglects the effect of the sun. Greenberg et al. (2) showed that before full-sized planets could form, the system evolved to a state where the two-body approximation is suspect due to very slow encounter velocities V compared with embryos' escape velocities V_e.

Criteria for validity of the two-body approximation were quantified by Wetherill and Cox (3,4) who found that the Öpik formulation (5) of the two-body method does break down for small V/V_e. Invalidity of the Öpik method means that other tools must be developed for estimating statistically the evolution of the planetesimal swarm. We now find that gravitational encounters can follow two-body behavior quite closely even under conditions where the Öpik formulation fails. Thus two-body methods other than Öpik's can be used to explore planet growth during the low-velocity era.

Our numerical experiments, which compare three-body integration of encounter behavior with various two-body approximation algorithms, show that the Öpik method often fails for reasons other than non-two-body behavior at encounter. Most commonly, distant perturbations long before encounter are responsible because they can grossly alter the parameters that describe the approach geometry from values assumed in the Öpik method.

We have developed a stategy for sorting out the various modes of failure (6), which uses a graphical display of enounter outcomes that is particularly well-suited to physical interpretation. Final velocities are shown relative to the "target plane", which is perpendicular to the relative velocity at encounter. Consider for example the case shown in Fig. 1, for an encounter of a planetesimal with a Mars-sized planet at 1 AU with $V/V_e = 0.6$. The Hill radius (one definition of the sphere-of-influence) is 0.005 AU. Initial conditions were chosen with the planetesimal 10 from the planet and with an eccentric, inclined heliocentric keplerian orbit such that the closest approach distance would be 0.01 if the keplerian orbit were fixed. Then a suite of other initial conditons were chosen with slightly different mean anomalies and pericenter longitudes, such that all the unperturbed keplerian orbits would pass at 0.01, all around the planet.

The set of initial keplerian trajectories form a beam that would symmetrically surround the planet, if the orbits remained fixed. In the Öpik formulation the encounter rotates each of the relative velocity vectors toward the planet. With our symmetrical beam, the post-encounter velocity vectors form a circle as projected into the target plane (top part of Fig 1). The bottom of Fig. 1 shows an edge-on view of that circle (+ is origin). Approach velocities were from left toward right and post-encounter velocities have been rotated by about 70° so as to form the circle. In this case, three-body numerical integration gave nearly the same results as the Öpik approximation.

The same procedure was followed for a suite of planetesimals with V/V_e = 0.2, but other parameters the same as in Fig.1. In this case the Öpik approximation still gives the circular distribution of post-encounter velocities (labelled PO, top of Fig. 2). The edge-on view of the circle is shown in the bottom of Fig. 2. Again the approach velocity was toward the right, but with the slower approach, velocity vectors are now rotated by about 150°.

For V/V_e so small, the true three-body behavior ("3B" in Fig. 2) differs from the Öpik approximation. However the results shown actually follow from two-body behavior at encounter. Analysis shows that distant perturbations well before encounter caused the entire beam of trajectories to pass well to one side of the planet, rather than to surround the planet as the unperturbed beam did. At encounter, the beam was then bent as a whole, like a rubber hose, by about 90°, in accord with two-body behavior. The result is the regular compact locus shown in Fig. 2.

This one example illustrates our general approach and the conclusion that, although the true three-body result may differ from the Öpik result, the encounter itself can be well approximated by two-body motion. Distant perturbations have proven to be very important in this context. They can actually prevent close encounters that the Öpik method would assume occurred. Horseshoe orbits are an example of such cases that must be understood, because they can substantially reduce accretion from a wide band within the feeding zone of a planetary embryo.

If distant perturbations are properly accounted for, the two-body approximation can be used in studies of planetary accretion, even in the very quiescent stage predicted by Greenberg et al. Such use may require that encounters offset by distant perturbations be statistically replaced and compensated by other perturbed trajectories. We also find that in some circumstances the two-body model must account for partial rotation of relative velocity vectors, rather than the full asymptote-to-asymptote rotation assumed in the Öpik formulation. Further studies are needed to find the true limits of the two-body approximation. Special attention needs to be focussed on close encounters of tangential and not-quite-crossing orbits, which are fairly probable and potetially deviate from two-body behavior.

References: (1) Safronov, V.S., NASA TT F-677, 1972; (2) Greenberg, R. et al., Icarus 35, 1, 1978; (3) Wetherill, G.W., and Cox, L.P., Icarus 60, 40, 1984; (4) Wetherill, G.W., and Cox, L.P., Icarus 63, 290, 1985 (5) Öpik, E.J., "Interplanetary Encounters" (Elsevier, Amsterdam), 1972; (6) Greenberg, R., Carusi, A., and Valsecchi, G.B., LPSC XVII, 287, 1986.

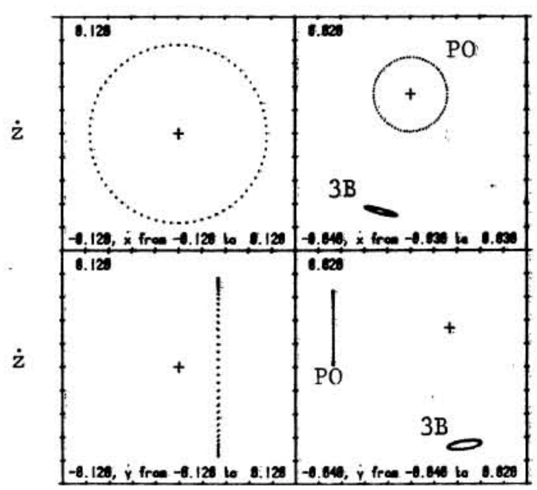

Fig. 1 Fig. 2