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Very early collisional evolution in the asteroid belt

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The asteroids probably experienced significant collisional evolution while the solar nebula was present. Planetesimals were brought into resonances with Jupiter by orbital decay due to gas drag. They were stirred to high eccentricities, resulting in hypervelocity collisions, while the non-resonant population was experiencing accretion at low velocities. Possible consequences include transport of bodies from the outer to inner belt, thermal processing and collisional disruption of planetesimals, and production of chondrules by shock waves.

1. Introduction

The history of the asteroids has been dominated by collisions. For most of the solar system's lifetime, the environment of the belt has been similar to the present one, with high orbital eccentricities and inclinations (hence relative velocities). Over the past 4.5 Gy, collisions have depleted the belt population, while disruption of a few large bodies created the observed Hirayama families (Hirayama, 1918; Marzari *et al.*, 1999). However, this is clearly not the entire story of the evolution of the asteroids. Plausible models of the solar nebula imply that the primordial surface density in the asteroid region was high enough to form a population of planetesimals with a total mass exceeding Earth's mass (Weidenschilling, 1977a). Numerical models of collisional evolution of the belt population (Davis *et al.*, 1985) have shown that its mass was not more than a few times the present value ($\sim 10^{-3}$ $M_\oplus$) at the time when velocities reached their present magnitude. Thus, most of the original mass was removed by some mechanism other than collisional disruption, and this removal occurred before or during the time when velocities were stirred up. There must have been an early period of accretional growth at low relative velocities, which was interrupted when velocities increased, and collisions became destructive. The stirring of velocities to their present high values, the depletion of most of the original mass, and the transition from accretion to disruption were surely due to the influence of Jupiter, although the exact mechanism is somewhat uncertain. One promising model for the depletion of the asteroid region was suggested by Wetherill (1992; see also Chambers and Wetherill, 2001). He proposed that runaway accretion produced large (Moon- to Mars-sized) planetary embryos in that region. Mutual gravitational encounters scattered them into resonances with Jupiter, which stirred up their velocities; the embryos in turn stirred up the smaller planetesimals (asteroids). The embryos were later ejected from the solar system by encounters with Jupiter, or collided with the terrestrial planets or the Sun. Sweeping secular resonances, which passed through the asteroid region during dissipation of the solar nebula (Nagasawa *et al.*, 2000), could also have stirred up eccentricities and inclinations.

The present paper deals with an earlier stage of evolution. It has generally been assumed that while the solar nebula was present, gas drag kept eccentricities of asteroid-sized planetesimals at low values, and that high velocities did not occur until the nebula had dissipated. However, the actual evolution of velocities was probably more complex. We will show that some asteroids could have attained high velocities while nebular gas was still present. Both low and high velocities occurred at the same time among similar asteroids at different heliocentric distances, and among bodies of different sizes at a given location. These phenomena permitted complex collisional histories for asteroids (or the planetesimals that were their parent bodies), including hypervelocity impacts and shock effects, accompanied by low-velocity accretion of fragments. This evolution could have led to migration of rather large planetesimals from the outer to inner region of the asteroid belt, and significant heating of their surface layers. Shock waves produced in the nebula by such bodies could also have been a source of chondrules.

2. Jupiter's Role

Jupiter, which is composed largely of hydrogen and helium, must have formed in the solar nebula. There are two main scenarios for the origin of the giant planets—nebular instability and core accretion. In the former, density perturbations in the nebula during its formation grew large enough to maintain themselves by self-gravity (Boss, 1997). In that model, gas giant planets formed before planetesimals. The latter mechanism assumes that planetesimals formed first, and runaway growth produced protoplanetary cores of rock and ice. If such a core reached a critical mass, of order 10 $M_\oplus$, it could accrete gas from the surrounding nebula (Pollack *et al.*, 1996). In either scenario, it is plausible that the solar nebula persisted for some time, perhaps several million years, after Jupiter's formation. During this interval,

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jovian perturbations and nebular drag could act together to affect orbits of planetesimals in the asteroid region.

Because the nebula was supported by a radial pressure gradient, it rotated at slightly less than the Kepler velocity. A planetesimal (or a solid body of any size) lacked this pressure support, and moved relative to the gas. Drag forces would have caused its orbit to decay, and it spiraled inward (Adachi *et al.*, 1976; Weidenschilling, 1977b). Such bodies in the asteroid region would eventually encounter commensurability resonances with Jupiter, at which the mean motions of planetesimal and planet are in the ratio of small integers. The strongest resonances are the 2:1 and 3:2 (located at heliocentric distances of 3.28 and 3.97 AU for Jupiter's present distance of 5.2 AU). At these locations the planet's perturbations are enhanced, and the planetesimal's eccentricity is raised. The outcome depends on its size, the nebular density, and the perturber's mass. Marzari *et al.* (1997) examined the effect of a proto-jovian core of 10 $M_\oplus$ on planetesimals encountering the 2:1 resonance, and showed that they passed through the resonance, while their eccentricities were pumped up to a few percent. Weidenschilling *et al.* (1998) showed that a fully-formed Jupiter with its present mass (317 $M_\oplus$) would have a much greater effect; moreover, outcomes of encounters with resonances could be qualitatively different. They identified two distinct mechanisms for planetesimal orbital evolution, associated with the two strongest resonances.

If Jupiter's orbit is assumed to be circular, bodies entering the 2:1 resonance have their eccentricities raised to moderate values of 0.1–0.2. After they pass through the resonance, gas drag causes their eccentricities to decay. However, if Jupiter has an eccentricity larger than about 0.03 (its present value is 0.048), a planetesimal may become trapped in the resonance. Its semimajor axis librates about the resonance, while its eccentricity is pumped up to large values (0.3–0.6). Eventually, the planetesimal escapes from the resonance. The drag force exerted by the nebular gas then causes the semimajor axis to decrease, while the eccentricity decays (Adachi *et al.*, 1976), and it ends up in a smaller orbit. An example of this evolution is shown in Fig. 1. For a low-mass nebula of a few percent of the solar mass, bodies larger than about 100 km diameter can be trapped in the 2:1 resonance, while smaller ones are damped too strongly or pass through the resonance too rapidly to be trapped. The trapping is stochastic, depending on the relative angular positions of the planetesimal and Jupiter at the time of encounter with the resonance. Marzari and Weidenschilling (2001) found the probability of trapping to be in the range 10–30%.

The second mechanism is associated with the 3:2 resonance; unlike 2:1 trapping, this mechanism changes semimajor axis and eccentricity simultaneously. A body encountering the 3:2 is excited to $e > 0.2$. This resonance is surrounded by many weaker, high-order resonances, which overlap in phase space at high eccentricities. Each resonance that the body encounters causes a stochastic change in *e*, which may result in an increase or decrease, depending on the values of the angular variables. Some bodies drop out and are damped into low-*e* orbits between the 3:2 and 2:1 resonances (orbital decay may eventually bring them to the 2:1 as described above, for another chance). Those that are "lucky" are boosted to still higher eccentricities, and gas drag passes them on to the next resonance. Eccentricities can grow to values as large as 0.5 by this process, while the semimajor axis decreases continually, without being trapped in any of the resonances. Marzari and Weidenschilling (2001) found that this mechanism works equally well if Jupiter's eccentricity is zero, or has its present value. They found about half of the bodies larger than 50 km diameter attained eccentricities greater than 0.4. Sunward of the 2:1, the resonances are weaker and more widely spaced, so those bodies eventually are damped to low eccentricities. Figure 2 shows an example of this kind of evolution.

Although these two mechanisms are distinct, their consequences are quite similar. Both can excite eccentricities up to values in the range 0.3–0.5, and transport asteroid-sized bodies from the outer to the inner belt. This migration

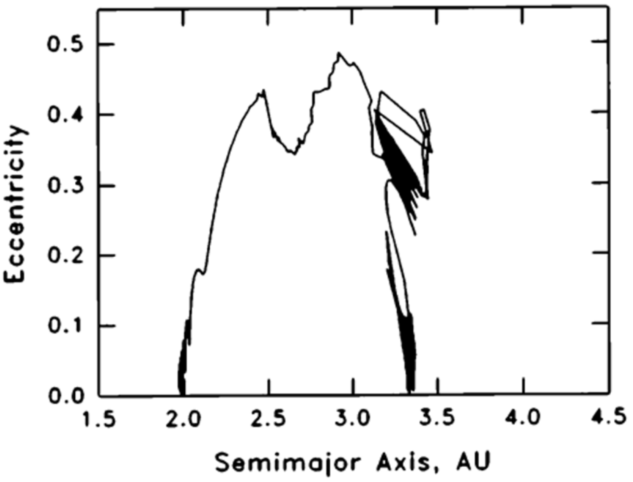

Fig. 1. Eccentricity vs. semimajor axis for a planetesimal of diameter 300 km encountering the 2:1 resonance with Jupiter. It is trapped in the resonance while *e* increases to nearly 0.5, then escapes, and gas drag causes the orbit to decay to near 2 AU. The total evolution time shown is 1.5×10^5 y.

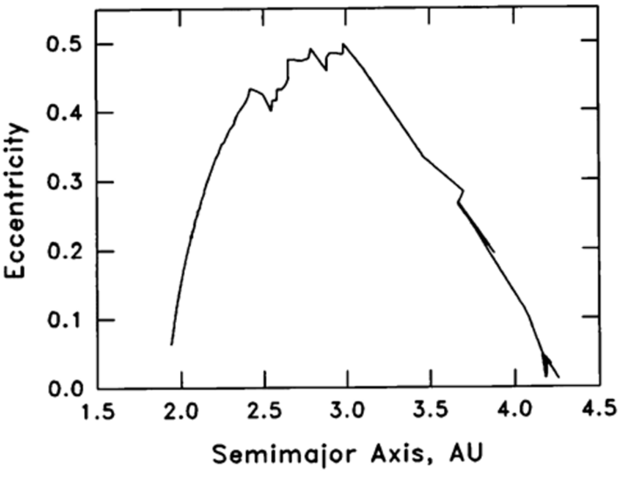

Fig. 2. Same as Fig. 1, for a 200 km planetesimal that encounters the 3:2 resonance. Multiple resonances increase *e* while the orbit decays. After passing through the region of resonances, eccentricity is damped by gas drag. The total evolution time is 7.5×10^4 y.

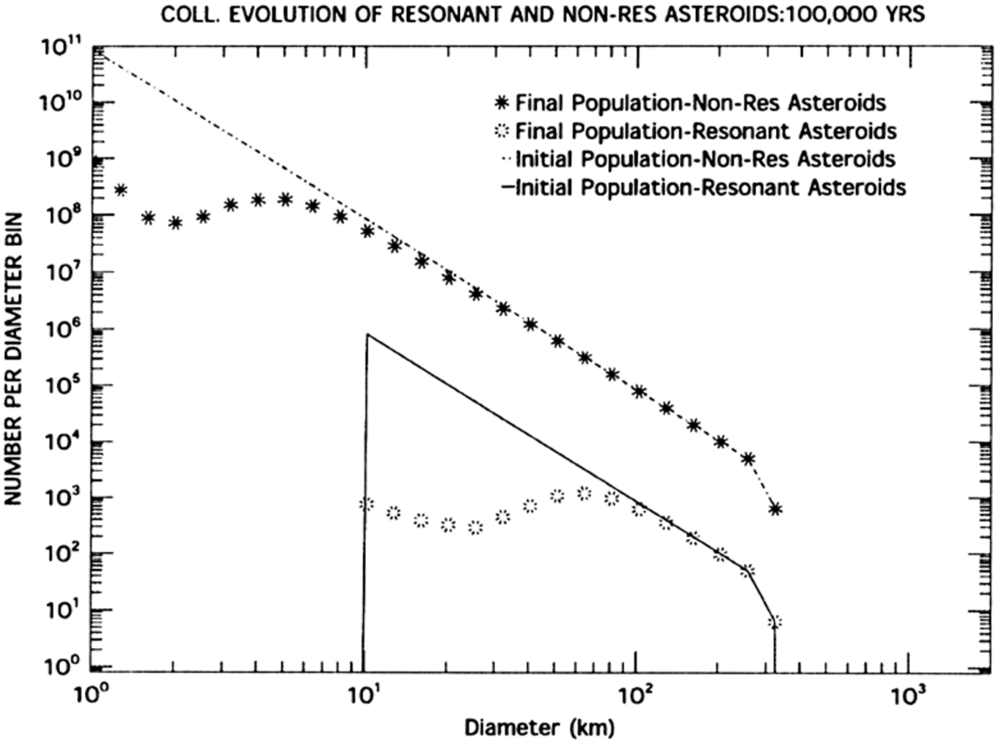

Fig. 3. Results of a collisional simulation involving two populations of asteroids: low-velocity (non resonant), and high-velocity (resonant). The non-resonant population contains 1 $M_\oplus$ of material, and the resonant population 0.1 $M_\oplus$. After 10^5 years of model time, the high-velocity population is depleted at sizes smaller than 100 km.

is much faster than the orbital decay due to non-Keplerian rotation of the nebula acting on a body in a circular orbit (Weidenschilling, 1977b); for eccentric orbits there is a term in the decay rate proportional to e that dominates at moderate eccentricities (Adachi *et al.*, 1976). An important feature of this orbital evolution is that inclinations remain low. Integrations performed in 3 dimensions show no increase in inclinations, even when eccentricities become large. There are two reasons for this outcome: resonant perturbations are dominantly in the orbital plane, and the rate of inclination damping by drag contains a term proportional to e, so higher eccentricities cause more effective damping of inclinations. For bodies a few hundred km in diameter, the time spent at high eccentricities is typically of order 10^5 y. The time spent trapped in the 2:1 resonance, and the migration time for the 3:2 crossing, are each proportional to the planetesimal size, and vary inversely with planetesimal size. The behavior of a body can be characterized by a single drag parameter that includes the gas density, planetesimal size and density, and drag coefficient; thus, a larger (smaller) body would have the same behavior in a more (less) massive nebula.

The nominal nebular model used in these simulations has a surface density of 4800 g cm^{-2} at distance $R = 1$ AU, and varying as $R^{-3/2}$; its total mass is 0.04 solar mass between 0.5 and 40 AU. Its temperature is assumed to be 640 R^{-1}° K, giving a fractional deviation of 4.65×10^{-3} from Keplerian rotation. The outcomes are not sensitive to the nebular parameters; simulations for a variety of nebular models yield similar results. We assume a laminar nebula, but note that planetesimals of kilometer size or larger would not be affected by turbulence. Of more concern is the possible effect of Jupiter on the nebular structure. Its perturbations might excite density waves or shocks in the gas at the 2:1 resonance; however, resonant planetesimals have such large eccentricities that they spend only a small fraction of each orbit near this location.

3. Consequences for Asteroid History

After Jupiter's formation, there would have been a period during which the asteroid region contained a sub-population of resonant bodies in highly eccentric orbits. While the time spent in resonance by any given body was probably short compared with the nebular lifetime, orbital decay would continually bring new bodies to the resonances, as long as gas was present in the asteroid region. This evolution would have been experienced mainly by bodies from a few tens to a few hundreds of kilometers in size, for which drift rates due to drag are of order 0.1 AU/My. Smaller bodies were damped too effectively by drag, while larger ones would not have time to reach the resonances during the lifetime of the nebula.

The high eccentricities of resonant bodies would result in very energetic collisions with non-resonant planetesimals. Their low inclinations would make such collisions highly probable. We would therefore expect the resonant objects to experience disruptive collisions with the more numerous background population. Figure 3 shows the result of a preliminary calculation of collisional evolution of a twocomponent population, using the collisional model of Davis *et al.* (1989). Here the undepleted non-resonant population, with mean $e = 0.03$, has a mass of 1 $M_\oplus$, with a power-law size distribution up to 300 km diameter. The resonant population, with $e = 0.3$, has 10% as much mass, and is truncated at a lower size of 10 km (smaller bodies would be damped by drag). Both populations have low inclinations of 1 degree. Their impact strength is 10^6 erg cm^{-3}. After a model time of 10^5 y, most of the resonant bodies larger than 100 km have survived, while smaller ones have been substantially depleted by collisions with the non-resonant population. In reality, larger bodies would spend more time at high velocities, so the probability of a resonant body's survival should be less dependent on size. More realistic modeling is needed, but this result suggests that bodies experienced significant collisional evolution during passage through resonance. Gas drag and resonant perturbations could in principle transport planetesimals from the outer belt to its inner region, but the survivors may have been few.

Resonant bodies move at high velocities relative to the gas; for high eccentricities there is a significant variation of the velocity of gas encountered during a single orbit. Figures 4 and 5 show the ranges experienced by the planetesimals in Figs. 1 and 2 (these are also approximate velocities relative to non-resonant bodies at corresponding heliocentric distances). Peak velocities are 8–10 km/sec. Such velocities are supersonic, and would produce shock waves in the nebular gas with Mach number 6–8, strong enough to melt small silicate particles; this mechanism may have produced chondrules (Weidenschilling *et al.*, 1998). The source material for chondrules would have been supplied by disruptive impacts between resonant and non-resonant bodies. Hypervelocity impacts would occur while most of the background planetesimal population experienced low-velocity accretional collisions. Chondrules and fragments, perhaps showing shock features, would be incorporated into still-accreting non-resonant bodies. In this model, chondritic meteorites are not truly "primitive," but are composed of "recycled" material from disrupted planetesimals. One important feature of such a scenario is that dust and chondrule-sized particles would be controlled by drag forces, not gravity, as accreting planetesimals moved through dust-laden gas. The accretion rate would be proportional to surface area rather than gravitational cross-section; thus most of the collisionally and thermally processed material would be accreted by the more numerous small planetesimals. If large protoplanetary embryos were present in the asteroid region during the lifetime of the nebula, they would have had relatively little effect on the evolution of the parent bodies of the asteroids that we observe today.

One consequence of the high velocities seen in Figs. 4 and 5 is heating of the surfaces of the resonant planetesimals. While the shocked gas could reach temperatures of thousands of degrees (probably buffered by dissociation of H_2), the low gas density results in lower surface temperatures. We estimate the heating rate by using the Rankine-Hugoniot relations for an ideal gas to compute the energy change across the bow shock as a function of Mach number, and assume the difference is radiated from the shock, with half the flux directed toward the planetesimal. We add to this the kinetic energy flux of the post-shock gas impinging on the surface, and equate the total to radiation from the surface to a background at the ambient nebular temperature. This yields maximum temperatures near 900°K; interestingly, the changing velocity and gas density result in cycling through several hundred degrees over a single orbit. While this process would affect only the outermost layer of a planetesimal, it could cause thermal processing of some meteoritic material.

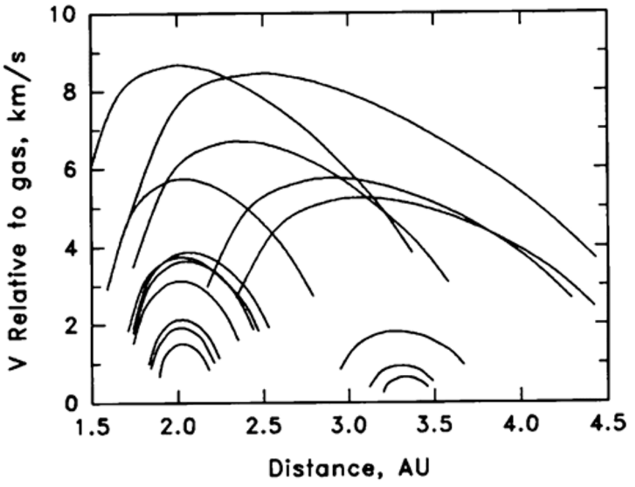

Fig. 4. For the case shown in Fig. 1, trapping in the 2:1 resonance of a 300 km planetesimal, its velocity relative to the nebular gas is plotted. Each curve shows the variation during an orbital period, from perihelion to aphelion, at intervals of 10000 y, during a total time of 1.5×10^5 y.

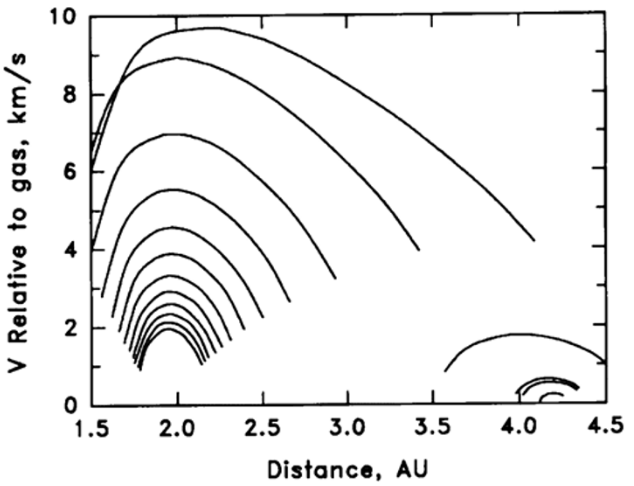

Fig. 5. Same as Fig. 4, but for the case of Fig. 2, of a 200 km planetesimal passing through multiple resonances. Curves of relative velocity are plotted at intervals of 5000 y, during a total time of 7.5×10^4 y.

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