ACCREPTION AND DYNAMICAL EVOLUTION OF ASTEROIDS AND COMETS.

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**Introduction:** We review our understanding of the formation and evolution of the small bodies of the Solar System from the theoretical point of view. The goal is to provide a context for the interpretation of the chronological and cosmochemical data obtained from the analyses of samples returned from these small bodies.

**Primary Accretion:** The accretion of rocky and icy planetesimals (the asteroids and comets of today's Solar System) is one of the most mysterious and controversial phases of Solar System history. A key unknown factor, which dominates the evolution of particles in the pre-planetesimal stage, is the degree to which the nebula was turbulent. Surface forces help small dust grains stick to each other, forming macroscopic fractal aggregates, that are presumably made progressively more compact by collisions [1]. How far planetesimals can grow in this way is unclear. If the nebula is turbulent, collisions may become disruptive as particles grow larger and relative velocities increase [2], stalling accretion around the meter in size. An additional severe problem is due to the drift of the growing particles towards the Sun, due to gas drag [3]. Bodies with sizes of order of a meter are removed from a region faster than they can grow up to sizes of a few kilometers, which are less sensitive to gas drag. This combination of problems is usually called the 'meter-size barrier' problem. While making sticking more difficult, turbulence helps us understand observations which suggest widespread mixing in the early nebula, such as the recent finding of high temperature, crystalline minerals in samples of comet Wild II returned by STARDUST [4,5].

To overcome the meter-size barrier and avoid uncertainties about 'sticking', it has been suggested that planetesimals might form quickly by gravitational instability, in a dense particle layer close to the nebula mid-plane [6]. However, these dense layers themselves generate local turbulence which disperses the particles and prevents gravitational instability [7,8]. Although the idea of classical gravitational instability has been recently resurrected in the context of very small particles [9,10], this latter scenario is invalidated by even tiny amounts of nebula turbulence [2].

Recent numerical simulations indicate several new and complex ways that nonlinear outcomes in 3D turbulence might create opportunities for accretion that were unknown more than a decade ago. Global, 3D turbulence might be produced by the magneto rotational instability [11] or by other, less well understood processes. Under nebula conditions, chondrule-sized particles can be concentrated by orders of magnitude into dense zones with particle density approaching the classical (but not, as it turns out, actual) threshold for gravitational instability [12,2], the fate of which has only recently been explored [13]. Also, the localized gas density and pressure maxima created by large eddies attract meter-size particles, which drift rapidly towards these regions of high pressure under gas headwinds or tailwinds generated by the opposed radial pressure gradients. It is therefore possible that, at specific locations of the disk, the concentration of solids is temporarily high enough to allow the formation of a large planetesimal due to a ‘local’ gravitational instability even in turbulence [14,15]. However, the role of inter particle collisions in this latter regime needs to be studied carefully.

**Collisional growth:** Once macroscopic planetesimals (tens of meters to kilometers) are formed, coagulation models [16,17] allow us to track the growth of the objects through their gravitational interactions and collisions. It should be noticed that these models fail to form a large number of Pluto-size bodies in the outer Solar System, whose past existence is inferred by a large number of constraints [18], as well as the cores of the giant planets. Therefore, some aspects of the growth of larger planetesimals and protoplanets are surely still missing in the theoretical models and numerical simulations. All models, however, agree in showing that the accretional process occurs faster at smaller distances from the Sun. Thus, it is likely that fully grown bodies existed in the inner Solar System, when the asteroid belt or the more distant disk where still dominated by dust particles. Because the differentiation of bodies is triggered by the decay of short-lived radioactive elements, it is likely that differentiated planetesimals were much...
more numerous in the vicinity of the Sun than further out in the disk. Quantifying the distance at which planetesimals could differentiate, however, is beyond the capabilities of the current models.

Dynamical evolution of planetesimals: The population of small bodies is strongly dynamical affected by the growth of the planets. As Jupiter and Saturn grew in a gas disk, they dispersed by close encounter the planetesimals originally in their vicinities. The largest objects, insensitive to gas drag, were mostly ejected from the Solar System, but some (such as the newly discovered object Sedna) could be perturbed into orbits typical of the Inner Oort cloud [19] due to the dense galactic environment present at that early time. The comet-sized bodies, however, were presumably circularized by gas drag just outside of the Jupiter-Saturn region and participated in the subsequent formation of Uranus and Neptune [20]. The planetesimals from the Uranus-Neptune zone were dispersed by the ice giant planets on a longer timescale, exceeding the gas disk lifetime. They formed the so-called scattered disk (the source of the current Jupiter-Family Comets) [21] and the outer Oort cloud (the source of the current Long Period Comets) [22].

In the framework of recent evolutionary models of the outer Solar System [23], both these two reservoirs of comets formed late, at the time of the so-called Late Heavy Bombardment (~700 Myr after planet formation), from planetesimals initially in the 15-30 AU region.

The asteroid belt was strongly affected during two evolutionary phases of the Solar System. First, during terrestrial planet formation, it underwent a substantial orbital excitation and dynamical depletion, due to the combined action of planetary embryos - originally formed in that region - and resonant perturbations exerted by Jupiter and Saturn [24-27]. During this phase, it is likely that fragments of differentiated planetesimals from the inner Solar System were implanted into the asteroid belt [28]. This may resolve the conundrum of the early differentiation age of some iron meteorite parent bodies [29]. It might be possible that some bodies of cometary nature from the Jupiter region were also trapped in the asteroid belt by a similar mechanism. Then, during the Late Heavy Bombardment of the terrestrial planets, the asteroid belt underwent a second dynamical excitation and depletion [23,30,31]. During this phase, some objects which originated in the trans-Neptunian disk could be captured in the outer part of the asteroid belt [32]. These objects are probably identified with the D and P type asteroids, which are numerous in the outer belt. In view of these results, the asteroid belt appears to be the reservoir of a population of planetesimals formed over a much larger range of heliocentric distances than its current radial extent would lead one to think. This has important implications for our understanding of the gradient of physical properties of planetesimals with heliocentric distance and for the nature of the planetesimal precursors of the terrestrial planets.

References: