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Forming giant planets and the collisional evolution of planetesimals: the cases of the Solar System and HD 163296

Diego Turrini (1)
(1) INAF-IAPS, Italy (diego.turrini@inaf.it)

Abstract

The formation of giant planets in circumstellar disks triggers a phase of dynamical excitation of the surrounding planetesimal disk. This phase of dynamical excitation is associated to an enhanced collisional evolution of the planetesimals, which in turn alters the compositional characteristics of both the planetesimals and the surrounding disk. Here we show how the effects of these processes on the composition of asteroid Vesta can be used to constrain the formation and migration history of Jupiter. In parallel, we show how the same processes acting in HD 163296's circumstellar disk result in the collisional production of second-generation dust that can explain both the observed amount and distribution of its dust population.

1. Giant planets and planetesimal dynamical excitation

Many fundamental steps of the planetary formation process take place while the young stars are still surrounded by their circumstellar discs. Among these are the settling of dust towards the median plane, the formation of planetesimals by dust accumulation, the growth of giant planets by planetesimal and gas accretion, and their possible orbital migration through interactions with the nebular gas (e.g.[1]). The formation of giant planets, in particular, is one of the milestones in the life of circumstellar disks, as their strong gravitational perturbations rapidly dynamically excite the surrounding planetesimals population. This phase of dynamical excitation is associated to an enhanced collisional evolution of the planetesimals and to the transport of different materials, particularly volatile elements, across the disk [2, 3, 4, 5, 6, 7, 8].

The mass growth of the giant planets is sufficient condition to trigger this phase of dynamical and collisional excitation of the planetesimals [2, 3, 6]. While not required to initiate it, migration nevertheless plays a major role in determining its intensity and the magnitude of its effects [2, 3, 6]. The implications of this phase of dynamical and collisional excitation for the early evolution of the Solar System have been recently investigated through asteroid (4) Vesta thanks to the data supplied by the NASA mission Dawn and by the HED meteorites [7]. In parallel, ALMA's observation of the circumstellar disk surrounding HD 163296, a 5 Myr old star of about 2 $M_\odot$ suggested to be orbited to at least three giant planets [14, 15, 16, 17, 18], allowed for the first time to search for the signatures of this process while it is possibly acting [8].

2. Jupiter's formation and Vesta's collisional evolution

Asteroid Vesta was confirmed by the Dawn mission as the source of the Howardite-Eucrite-Diogenite (HED) family of basaltic achondritic meteorites [10, 11], whose members possess some of the oldest formation ages among the known meteorites (e.g. [9]) and predate the formation of Jupiter [7]. The data provided by the Dawn mission revealed that the basaltic crust of Vesta, the source region of HEDs, globally survived the collisional history of the asteroid [12]. In parallel, laboratory analyses of the HED meteorites constrained the limited presence of water within Vesta's primordial crust [13] and the possibile signature of the late accretion of Vesta's crust in the form of an overabundance of highly-siderophile elements [9].

The phase of dynamical and collisional excitation of the planetesimal disk triggered by Jupiter's formation was shown to result in an early bombardment on asteroid Vesta while its crust was still molten [2, 7]. As a result, impacts stripped HED material from Vesta's primordial crust while at the same time enriching it in water and highly-siderophile elements. We investigated whether the data provided by Dawn and the HEDs on the composition of Vesta's crust could be used to constrain its collisional evolution and, consequently, the migration of Jupiter and the characteristics of the planetesimal disk [7].

Our results show that the global survival of Vesta's crust to impacts can be used to rule out violent collisional scenarios characterized by numerous high-energy impacts [7]. The abundances of water and highly-siderophile elements in HEDs, instead, appear to be sensitive to the extent of Jupiter's migration and to the size frequency distribution of the planetesimals respectively [7]. The joint use of these three constraints from Vesta results in a powerful tool to quantitatively compare different formation and migration scenarios for Jupiter and the giant planets [7].

3. HD 163296 and planetesimal collisional dust production

Notwithstanding its age, alongside its giant planets HD 163296's disk still possesses a high dust-to-gas ratio [14], with the dust distribution diverging from what would be expected from hydrodynamic simulations in the region inside the innermost giant planet [14]. Mature disks like HD 163296 are expected to contain invisible yet massive populations of planetesimals whose dynamical and collisional evolution will be sculpted by the growing gravitational perturbations of the forming giant planets [2, 3]. We investigated the dynamical and collisional excitation of HD 163296's planetesimal disk resulting from the formation of its giant planets to test whether it can result in a significant collisional production of second-generation dust that could explain the observed behaviours [8].

Our results indicate that the dynamical excitation process caused by the formation of HD 163296's giant planets and the associated collisional dust production can be responsible for a large fraction, if not the entirety, of the current dust in HD 163296's circumstellar disk [8]. Based on the gas and dust density profiles reconstructed by [14] about 70 $M_\oplus$ of dust should be injected into the orbital region inside the innermost planet to explain the observations. According to our results, the dynamical excitation process can produce the required amount of second-generation dust in 1-3 Myr depending on the specific planetary masses and size-frequency distribution of the planetesimals. Our results suggest that these processes represent a common evolutionary phase for circumstellar disks hosting forming giant planets within a planetesimal disk [8].

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