Letter to the Editor

Second-generation dust produced by the formation of giant planets in circumstellar discs.

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ABSTRACT

Context. The observational capabilities of ALMA are providing an unprecedented view of the structure and properties of circumstellar discs, revealing for the first times the signatures left in their gas and dust by the formation of giant planets. By the time giant planets form, however, planetesimals should still contain a significant fraction of the solid mass initially present in the disc and their dynamical excitation by the planetary perturbations should lead to a significant collisional dust production.

Aims. We investigate the dynamical and collisional evolution of the planetesimal population in HD163296’s circumstellar disc across the formation of its three giant planets to assess whether the second-generation dust produced by the planetesimal collisions could refill the disc with dust, formerly depleted by the planetary formation process, and produce potentially observable features.

Methods. We use N–body simulations together with statistical methods developed for the study of the asteroid belt in the Solar System to estimate the dynamical and collisional response of the planetesimal population to the formation of HD163296’s three giant planets. We took advantage of impact experiments and scaling laws to assess the outcome of the collisions among the planetesimals.

Results. Our results show that the formation of HD163296’s giant planets should be followed by a global phase of dynamical excitation of the planetesimals inhabiting the circumstellar disc. This dynamical excitation would produce a violent collisional environment across HD163296’s disc that should still be active today. The high impact velocities associated to this excited environment would cause a tenfold-to-hundredfold increase in the dust production by impacts, with a predicted peak in the region interior to the inner planet in qualitative agreement with observational data. The excited velocities of the planetesimals could result in the release of transient, non-equilibrium gas species like H\textsubscript{2}O due to ice sublimation during impacts and, being supersonic with respect to the gas, could also produce bow shocks in the gas, possibly causing a broadening of its emission lines.

Conclusions. Our investigation of HD163296’s system suggests that the dynamical and collisional excitation caused by giant planet formation represents a common evolutionary process in circumstellar discs hosting this kind of planets. As the intensity of this process strongly depends on the masses of the giant planets, the detection, or lack thereof, of dust regeneration and of non-equilibrium species in circumstellar discs can help constraining the planetary masses.

Key words. protoplanetary disks – planets and satellites: gaseous planets – planets and satellites: formation – planets and satellites: dynamical evolution and stability – accretion, accretion disks

1. Introduction

Many fundamental steps of the planetary formation process take place during the lifetime of circumstellar discs, among which 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 (see e.g. Morbidelli & Raymond 2016 for a recent review).

It is expected that both the density and size distribution of the original dust, present in the disc at the beginning of the settling process, will significantly change during the disc evolution timescale. The accretion of dust into planetesimals and planets will lead to a progressive decrease of its density with the disc’s age (Pascucci et al. 2016), in particular at small sizes. Thus, the dust depletion should peak at the time when the giant planets reach their final mass and finally clear the region from the remaining dust.

Once formed, however, giant planets drastically alter the dynamical equilibrium of the surrounding leftover planetesimals by exciting their orbits through resonances and planetary encounters (Turrini et al. 2011, 2012; Turrini 2014; Turrini & Svetsov 2014; Turrini et al. 2015; Raymond & Izidoro 2017). This excitation process acts in response to the mass growth of the giant planets, independently of whether the planets migrate or not (Turrini et al. 2011, 2012; Turrini 2014; Turrini & Svetsov 2014; Turrini et al. 2015; Raymond & Izidoro 2017).

This phase of dynamical excitation greatly enhances the collisional activity among the planetesimals (Turrini et al. 2012). The energetic collisional evolution of the planetesimals, characterized by cratering and fragmentation events (Turrini et
al. 2012), halts and reverses the progressive decline of the dust density causing a sudden increase in the dust production rate.

This process of dust regeneration should produce two observable phenomena. The first is a sudden increase in the dust density after a period of steady decrease. Given that the dust density in observed discs depends on the stellar age (Pascucci et al. 2016), such an increase could be detectable as a deviation from the expected trend. The second phenomenon is the appearance of high-density dust structures in the disc that could be related to the location of the giant planets triggering the second-generation dust production.

Recent ALMA observations of HD163296’s circumstellar disc with a spatial resolution of 25 au showed three distinct gaps in the dust distribution of the disc suggesting the presence of at least three giant planets (Isella et al. 2016). Current observations indicate they orbit approximately at 65, 105 and 160 au from the central star and have fiducial masses of the order of 0.1, 0.3 and 0.3 Jovian masses (Isella et al. 2016). The age of HD163296, an intermediate mass star of 2.3 M⊙, is of about 5 Myr (Isella et al. 2016), indicating that the system is evolved and characterized by the coexistence of dust, gas, planetesimals and planets.

In the present letter, we focus on this system since it should have undergone or even still be undergoing the dynamical excitation phase caused by the mass growth of its giant planets. Our goal is to explore the dynamics of planetesimals orbiting nearby the giant planets and evaluate the changes in their collisional speeds to test if indeed their enhanced collisional evolution can lead to the production of second-generation dust in this system. This would be consistent with the detection of a significant amount of dust in the proximity of the planets, in spite of the evolved stage of the disc.

2. Numerical methods

Our investigation is based on the results of N-body simulations we performed using a version of the hybrid symplectic algorithm of the MERCURY 6 software (Chambers 1999) we modified to account for migration and planetary growth. The simulations considered a set of planetary systems composed of the central star, the three forming giant planets, and a disc of planetesimals modelled as massless particles, analogous to the HD163296 system as observed with ALMA.

In this first study no migration was assumed to occur during the formation of the giant planets. The initial orbits of the giant planets were characterized by semimajor axes identical to those estimated by Isella et al. (2016), assumed to be coplanar and with initial eccentricities of the order of 10−3. The initial orbits of the planetesimals were characterized by eccentricities and inclinations (in radians) of the order of 10−2.

During the first τc = 106 years of the simulations the giant planets accreted their cores, whose masses grew from an initial value of M0 = 0.1 M⊕ to the critical value Mc = 15 M⊕ as:

$$M_P = M_0 + \left(\frac{e}{e-1}\right) (M_c - M_0) \left(1 - e^{-t/\tau_c}\right)$$

(1)

consistently with the mass growth profiles in previous studies of Jupiter’s formation (see e.g. Lissauer et al. 2009 and D’Angelo et al. 2011 and references therein) and in the pebble accretion scenario (Bitsch et al. 2015).

After the critical mass value Mc was reached, the mass growth of each giant planet during the subsequent gas accretion phase was modelled as:

$$M_P = M_c + (M_f - M_c) \left(1 - e^{-t/\tau_f}\right)$$

(2)

where M_f is its final mass estimated by Isella et al. (2016). An e-folding time of $\tau_c = 1 \times 10^5$ years was chosen based on the results of the hydrodynamical simulations described in Lissauer et al. (2009) and in Coradini et al. (2010) and D’Angelo et al. (2011) and references therein.

We performed three different simulations to estimate how the details of the mass growth of the giant planets affect the end results. In the first simulation, representing our reference case, the final masses for the giant planets were identical to those estimated by Isella et al. (2016). In the second simulation the giant planets reached the same final masses but the mass growth took place 20 times faster. In the third simulation the mass growth proceeded at the same speed as in the first simulation but the final masses of the giant planets were twice as large.

The orbital elements of the giant planets and the massless particles were recorded every 107 years. The output of the simulations was used to study the evolution of the circumstellar collisional environment in response to the mass growth of the giant planets. For this task we took advantage of the well-tested collisional methods that have been extensively used to study the evolution of the asteroid belt in the Solar System (see e.g. O’Brien and Sykes 2011 and references therein, Turrini et al. 2012).

Specifically, we used the numerical algorithm originally developed by Wetherill (1967) and expanded by later works (see Greenberg et al. 1988; Farinella & Davis 1992) to calculate the evolution of the average impact velocities among the planetesimals across the circumstellar disc as a consequence of their enhanced dynamical excitation. The evolution of the impact velocities then allows us to estimate the increase in the efficiency of impacts in eroding mass from the planetesimals and introducing new dust in the disc in the form of impact ejecta.

To estimate the erosion efficiency of impacts, we took advantage of the scaling laws developed over decades of study of cratering events in the Solar System (see Holsapple and Housen 2007; Svetsov 2011 and references therein) and in particular of the relation between impact velocity and eroded mass for rocky and icy targets (Holsapple and Housen 2007) in the following form averaged over all possible impact angles (Svetsov 2011):

$$m_e/m_p = 0.03 \cdot \left(v/v_{esc}\right)^{1.65} \cdot (\rho_t/\rho_p)^{0.2}$$

(3)

where $m_e/m_p$ is the eroded mass normalized to the projectile mass, $v$ and $v_{esc}$ are the impact velocity of the projectile and the escape velocity from the target, and $\rho_t$ and $\rho_p$ are the target and projectile densities, which we assumed to be both equal to 1 g cm−3 thus cancelling out the last term on the right side of Eq. 3.

3. Results

Fig. 1 depicts the state of the simulated system after 5 Myr of dynamical evolution, i.e. a possible present state for HD163296’s disc. As is immediately visible, the gravitational perturbations of the giant planets carved not only the observed gaps in the gas and/or the dust (Isella et al. 2016) but also gaps in the planetesimal disc (see Fig. 1, top panels and bottom left panel).

The carving of the gaps in the planetesimal disc resulted in the formation of a population of scattered planetesimals on highly eccentric and/or inclined orbits (Fig. 1, top right and bottom left panels). In parallel, the giant planets created a network of resonant regions across the disc through which they dynamically excited the orbits of the planetesimals outside the gaps (see Fig. 1, top right and bottom left panels). Both populations of dynamically excited bodies cross larger orbital regions than their non-excited counterparts and can impact against the latter
Fig. 1. Dynamical state of the planetesimal disk of HD163296 in our reference case after 5 My due to the excitation caused by its three giant planets. Top left: ‘face-on’ orbital structure and density distribution of the planetesimals. Note the gaps and the fine-scale pattern of over-dense and under-dense regions created by the giant planets. Top right: orbital eccentricities of the planetesimals in the excited circumstellar disc. Bottom left: orbital inclinations of the planetesimals in the excited circumstellar disc. Bottom right: radial distribution of the impact velocities among planetesimals throughout the excited circumstellar disc. The color code indicates the probability distribution of the impact velocities.

at higher velocities than those characteristic of the initially unperturbed disc (see Fig. 1, bottom right panel, and Fig. 2).

Because of the gravitational perturbations of the growing giant planets, the distribution of the relative impact velocities among planetesimals spread from the initially compact one characterized by velocities not exceeding 100 m s\(^{-1}\) throughout most of the disc (see Fig. 2, top panel) to a more diffuse one reaching peak values exceeding 4 km s\(^{-1}\) (see Fig. 1, bottom right panel, and Fig. 2, central panel). Adopting reference impact velocities of 100 m s\(^{-1}\) for the initially non-excited planetesimals and of 1-3 km s\(^{-1}\) for the excited ones, Eq. 3 allows to calculate that the erosion efficiencies of impacts (and the associated dust production rates) would grow by a factor of 50-300 due to the perturbing effects of the giant planets.

Due to the range of values spanned by the enhanced impact velocities, the amount of material stripped from the planetesimals by impacts is not the only factor affected by the process of dynamical excitation. Impact experiments on ice (Stewart et al., 2008) reveal that also the physical state of the eroded material is affected. Impact velocities below 1 km s\(^{-1}\) are expected to cause the icy component of the planetesimals to be preferentially excavated instead of vaporized (Stewart et al., 2008). As such, a large number of collisions (see Fig. 2, middle panel) in the dynamically excited disc will produce second-generation refractory and icy grains that will enrich the surviving first-generation original dust population of the disc.

For impact velocities above 1 km s\(^{-1}\), impacts will melt and vaporize increasingly larger fractions of the icy component of the planetesimals (Stewart et al., 2008). Through this process, most energetic impacts (see Fig. 2, middle panel) will release in the disc gaseous species not in local thermal equilibrium with the surrounding gas, most notably H\(_2\)O and NH\(_3\) as hinted by Herschel’s observations of the circumstellar disc of TW Hya (Salinas et al. 2016). While non-equilibrium species are expected to be transient and to freeze-out on relatively short timescales, it has been argued that collisions among planetesimals might sustain their continued presence beyond their respective ice condensation lines provided that impact rates are sufficiently high (Salinas et al. 2016).

Finally, an additional effect of these high eccentricity–high inclination planetesimals moving supersonically with respect to the gas is the generation of shock waves in the gas of the disc (Weidenschilling et al. 1998). The high temperatures of the gas at the shocks may lead to the broadening of emission lines, which could be an observable test for the presence of supersonic planetesimals. In addition, according to Tanaka et al. (2013), the heating and resulting evaporation of the planetesimal surfaces at bow shocks would shrink the bodies. The subsequent cooling of the vapor produced in this way would form dust particles by recondensation, which would contribute to the formation of second-generation dust.

The faster growth experienced by the giant planets in our second simulation did not change in any significant way the qualitative picture described by our reference case. The larger final masses of the giant planets in our third simulation, instead, caused a marked change in the distribution of the impact velocities (see Fig. 2, bottom panel). Specifically, the distribution of the impact velocities became shallower and wider, reaching
The results of our investigation indicate that the formation of HD163296’s three giant planets should have triggered a phase of dynamical excitation of its leftover planetesimal population, analogous to that suggested by previous studies focusing on the Solar System (Turrini et al. 2011, 2012; Turrini 2014; Turrini & Svetsov 2014; Turrini et al. 2015; Raymond & Izidoro 2017).

This excitation would create a globally violent collisional environment and result in tenfold-to-hundredfold increases in the dust production rates by impacts. This enhanced dust production would create a second-generation of dust in the circumstellar disc, whose original dust population was previously depleted by the process of planetary formation. This second-generation dust distribution may be decoupled from the gas density since it is related to the planetesimal collisions and impact velocities.

While the uncertainties on the distributions of gas and dust, hence on the masses and possibly the number of the giant planets (Isella et al. 2016), make quantitative comparisons difficult, our results suggest that the dust production should peak immediately inside the inner gap in the dust distribution, over a region a few tens of au wide, due to the higher impact velocities (see Fig. 2). This is in good qualitative agreement with the decreased gas-to-dust ratio found by Isella et al. (2016) in the same orbital region with respect to what dynamical models of the disk containing only gas and dust would predict (see their Fig. 2, right panel).

Our results also raise the possibility for observational signatures of this excitation process in the gas of the disc. First, most energetic impacts could cause the sublimation of the icy component of the planetesimals and release transient, non-equilibrium gas species like H$_2$O in the disc (Salinas et al. 2016). Second, excited planetesimals would move at supersonic speeds with respect to the gas and form bow shocks (Weidenschilling et al. 1998). This process could produce observable signatures by broadening the emission lines of the shocked gas. These bow shocks may also contribute to the dust regeneration by ablating the planetesimal surfaces (Tanaka et al. 2013).

Finally, looking beyond the specific case study of HD163296 our investigation suggests that dust regeneration is spontaneously triggered by the mass growth of giant planets. As such, it may represent a common evolutionary process in circumstellar discs hosting forming giant planets, as originally suggested by Turrini et al. (2012). This would offer a possible explanation of why also relatively old discs still have a significant dust population in spite of the coagulation and accretion processes.

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