The ablation barrier for the growth of metre-size objects in protoplanetary discs

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ABSTRACT

Ablation is a destructive process which can erode small-size planetary objects through their interaction with a gaseous environment. Ablation operates in a wide range of environments and under various conditions. Ablation has been extensively explored in the context of atmospheric entries of meteorites into Earth-atmosphere and planetesimal ablation in gas-giant planetary envelopes. Here we show that ablation of pebbles and small planetesimals in protoplanetary-discs can constitute a significant barrier for the early stages of planet formation. We use analytic calculations to show that under the conditions prevailing in protoplanetary discs small bodies (decimetres – tens of metres) are highly susceptible to gas-drag ablation. At this size-range ablation can efficiently erode the planetesimals down to few-cm size and quench any further growth of such small bodies. It thereby raises potential difficulties for channels suggested to alleviate the metre-size barrier. Nevertheless, the population of ∼ decimetre-size pebbles resulting from ablation-erosion might boost the growth of larger (> km size) planetesimals and planetary embryos through increasing the efficiency of pebble-accretion, once/if such large planetesimals and planetary embryos exist in the disc.

Key words: comets: general – minor planets, asteroids: general – planets and satellites: formation

1 INTRODUCTION

The growth of dust aggregates and sub-cm size pebbles in protoplanetary-discs can be understood theoretically and experimentally (Wurm & Blum 1998). The growth of km-size objects or larger planetesimals and planetary embryos could also be efficient, and possibly proceed through mechanisms such as a pebble-accretion (Ormel & Klahr 2010; Perets & Murray-Clay 2011; Lambrechts & Johansen 2012). However, the growth of pebbles/boulders in the intermediate regime from ~cm to metre up to km-size planetesimals is not well understood. Several physical processes potentially quench planetesimal growth in this size range. These growth-barriers include fast radial-drift of (typically) metre-size bodies (at AU scales, and smaller at larger distances) into the host star (Adachi et al. 1976; Weidenschilling 1977); and inefficient growth of dust-aggregates/pebbles due to collisional fragmentation and erosion (Blum & Wurm 2000; Brauer et al. 2008; Birnstiel et al. 2010; Güttler et al. 2010; Krijt et al. 2015), leading to the so-called metre-size barrier.

Several solutions to the metre-size barrier have been proposed, including particle trapping eddies, (Klahr & Henning 1997), (instability MRI-driven turbulent discs near the snow-line (Brauer et al. 2008), and collisional growth (Windmark et al. 2012). The streaming instability (Youdin & Goodman 2005; Johansen & Youdin 2007) is a promising route to planetesimal formation, although it requires fine tuned conditions, such as large initial metallicity (see recent review by Blum (2018), and references therein). Recently, Grishin et al. (2019) have suggested that planetesimals can be exchanged and captured between protoplanetary discs, some of them already on ∼ km-size scale. Only a tiny fraction of protoplanetary discs are required to form planetesimals in-situ in order to "seed" the entire birth cluster with planetesimals. Thus, the formation of the first planetesimals can be an exponentially rare event, consistent with the various fine-tuned models for planetesimal formation. Pfalzner & Bannister (2019) had suggested to take the seeding model one step further and start with a population of planetesimals already at the stage of star formation and collapse of giant molecular clouds.

Here we identify an additional, ablation-induced barrier for planetesimal growth. This physical process efficiently erodes bodies in the size range of 10 cm–10 m metre embedded.
in the gaseous protoplanetary-disc. It thereby challenges several of the currently suggested solutions to the metre-barrier problem, and hinders the growth of small-bodies even under favourable conditions. Ablation in protoplanetary-discs, currently not included in dust and planetary standard growth models, significantly affects the evolution and growth of sub-km bodies embedded in the discs and their size distribution. Destructive processes of objects in discs were discussed from the experimental point of view (Paraskov et al. 2006; Demirci et al. 2019; Schräpler et al. 2018). However, due to experimental constraints, the experiments included focused on small objects for short timescales of about an hour – and then scaled-up the results. Here we consider slow ablation, which might not be measured in these experiment due to its limited measured timescales, but has a significant cumulative effect.

Ablation is a destructive process, caused by the gas flow around a solid object leading to the removal of mass from its outer layer, due to several possible processes. Ablation is discussed widely in the context of meteoroids entry to the atmosphere (Opik 1958; Rogers et al. 2005). During the entry, the temperature difference between the meteoroid and its environment induces thermal ablation, i.e. evaporation of the outer layer. Another type of ablation observed in meteoroids is sputtering which is a single atom displacement of the outer layer. Another type of ablation observed in meteoroids is sputtering which is a single atom displacement of the outer layer. Another type of ablation observed in meteoroids is sputtering which is a single atom displacement of the outer layer.

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$$v_{relx} = \frac{2\eta v_k St}{1 + St^2}, \quad v_{rely} = -\eta v_k \left(\frac{1}{1 + St^2} - 1\right)$$

The Stokes number is defined by

$$St = \frac{\Omega_{stop}}{F_D}, \quad t_{stop} = \frac{mv_{rel}}{F_D}$$

where $\Omega$ is the angular Keplerian velocity. $F_D$ is the drag force (see Equation 1). For the drag coefficient, we adopted the fitting from Perets & Murray-Clay (2011)

$$C_D(Re) = \frac{24}{Re} (1 + 0.27 Re)^{0.43} + 0.47 \left[1 - \exp\left(-0.04 Re^{0.38}\right)\right]$$

The drag coefficient function encapsulates the drag law, which can be divided into three main regimes, ram-pressure, Stokes and Epstein regimes (Weidenschilling 1977). In the ram pressure regime, $Re \gg 1$, $C_D \approx 0.47$, while in the Epstein regime, $Re \ll 1$, $C_D \rightarrow 24/Re$. The intermediate regime is the Stokes drag, where $1 < Re < 800$ and $C_D \propto Re^{-3/5}$. The transition between the regimes occurs at $Re = 1$, and can be rephrased equivalently in terms of Stokes number and relative-velocity.

Figure 1 shows the Stokes and Reynolds number are an increasing function of the size of the object. Stokes and Reynolds numbers correspond to the coupling to the gas in the disc, which becomes weaker for larger objects.

Given the strong dependence of the ablation rate on the relative-velocity, the density profile of the disc, the appropriate (size dependent) Stokes and Reynolds numbers as well as $\eta$ play a significant role in modeling ablation. The peak

$$F_D = \frac{1}{2} C_D(Re) \pi R^2 \rho_k v_{rel}^2$$

where $R$ is the radius of the object and $v_{rel}$ is the velocity of the object relative to the gas. The drag coefficient, $C_D$ depends on the specific conditions, including the particle size and the relative particle-gas velocity. For spherical bodies, the drag coefficient depends only on the Reynolds number $Re$.

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of relative-velocity is $\sim \eta v_{\text{rel}}$, and henceforth even a small difference in $\eta$ can introduce significant changes in the ablation rate. The ablation dependence can be non-trivial, due to the mutual dependence of the relative velocity and the Stokes number (see A for further details).

### 2.2 Timescales of Ablation in discs

The rate of gaseous-mass interaction with the particle depends on the geometric cross section for the particle, the gas density and the relative velocity; $\pi R^2 \rho_g |v_{\text{rel}}|$. Generally, the cross-section varies with Reynolds numbers and the area exposed to shear stress (Paraskov et al. 2006). The specific kinetic energy transferred to the particle by the coupling to the gas is then $\propto v_{\text{rel}}^2/2$, up to an efficiency factor $f_E \propto C_D$. The proportionality can be derived from the work done by the gas drag, $F_D \propto v_{\text{rel}}$ or equivalently $f_E \propto R^2 \rho_g |v_{\text{rel}}|$ (see detailed derivation in Podolak et al. 1988). The efficiency of the gaseous kinetic energy transfer to the particle can also be expressed in terms of $C_h$ and $Q$; the heat transfer coefficient and the latent heat, respectively. For small objects, cohesive and gravitational forces might play an important role as well (Demicici et al. 2019; Shao & Lu 2000). Generally, the decrease in the radius $R$ of an object with a given density $\rho_p$ only due to gas drag (i.e. neglecting the temperature gradient) is Pinhas et al. (2016); Valletta & Helled (2018)

$$\frac{dR}{dt} = \frac{C_h \rho_g}{2Q \rho_p} |v_{\text{rel}}|^3. \quad (5)$$

The timescales for the ablation of an object to half its size can be approximated by

$$t_{\text{abl}} = \frac{R}{|v_{\text{rel}}|} = \frac{2Q \rho_p R}{C_h \rho_g |v_{\text{rel}}|^3}. \quad (6)$$

Unless stated otherwise, we consider the ablation of pebbles with $\rho_p = 3.45 \text{ g/cm}^3, Q = 8.08 \times 10^{10} \text{ erg/g}$ (Pollack et al. 1996). These parameters were taken as typical parameters of rocky pebbles. See detailed discussion about the ablated materials in Appendix B. Our disk models follow those used in our previous papers (Perets & Murray-Clay 2011; Grishin & Perets 2015) where the gas-pressure support parameter is $\eta \approx 10^{-3}(a/\text{AU})^{3/7}$ and the temperature profile is $T = 120(a/\text{AU})^{-3/7}$.

In Figure 2, we show the characteristic timescales determined by Equation (6). At a fixed distance from the center of 1AU, ablation is most effective around $\sim 10^2 \text{ cm}$, and the embedded objects can be ablated down to half its size under $\lesssim 0.1 \text{ Myr}$. More generally, objects in the size range of $\sim 10^{-5} \text{ cm}$ can be ablated down to half their initial radii over a typical lifetime of a protoplanetary-disc or less.

The contour plot reveals the distance-object-size ($a$-$r$) regime in which the ablation leaves a significant mark in less than the disc lifetime. Ablation can still be efficient in affecting object positioned up to 5 AU from the star, and can significantly affect even objects as large as $\sim 10^5 \text{ cm}$ (at distances smaller than $\lesssim 2 \text{ AU}$). In other words, efficient ablation operates over a significant parts of the disc and affects a wide size-range of embedded objects.

### 2.3 Dynamical Evolution

In order to examine the evolution of objects under the influence of ablation, we integrate Equation (5) numerically using a Runge-Kutta integrator. Figure 3 presents the time evolution of objects with various initial radii and distances from the star.

Ablation of larger objects of $\sim 10^2 - 5 \times 10^3 \text{ cm}$ is a relatively slower process; these ablate to $\sim 10^2 \text{ cm}$ size over a few Myr. Once the object is eroded down to metre-scale size, its ablation is significantly accelerated and it evolves much more rapidly. We find that bodies with initial metre-size are ablated significantly up to $\sim 5 \text{ AU}$ from the star. We checked even larger objects, and got ablation fractions of few percents per 100 period times, which are in agreement with the results of D’Angelo & Podolak (2015).

As can be seen in Figure 3, given sufficient time, the embedded-bodies are eventually eroded to some typical final size, at which point the bodies are strongly coupled to the gas, the relative velocity between the objects becomes very low, and the $|v_{\text{rel}}|^3$ dependence of the ablation on the velocity quenches any significant further ablation.

### 3 RELATIONS BETWEEN ABLATION AND OTHER PROCESSES IN DISCS

Other physical processes occur and potentially couple to the effects of the ablation, in particular turbulence and radial-drift could play an important part in the evolution of pebbles. In the following we discuss some of these aspects. Radial-drift due to gas drag is one of the most dominant processes in the disc. It can potentially lead to inspiral of the pebbles/planetesimals towards the star and their possible destruction over short thousands to tens of thousands of years timescales.

In a steady state, the equations of motion in the presence of gas drag can be solved self-consistently (e.g. Perets & Murray-Clay (2011)). The radial-drift is given by steady-state solution of the radial velocity:

$$\frac{da}{dt} = -v_r = -\frac{2\eta v_r St}{1 + St^2} \quad (7)$$

MNRAS 000, 1–7 (2019)
Figure 2. The characteristic time-scales for the ablation of an object to half of its initial radius. Left: Different initial radii, for fixed distances from the host star. Right: A contour plot for the characteristic ablation time-scales for a range of initial radii and distances from the center. The characteristic times are given as labels on the contour lines in units of Myr.

Figure 3. The evolution of the size of objects embedded in the protoplanetary-disc due to ablation. Left: Dependence of the evolution on the initial radii of the bodies at a fixed distance of $a = 1$ AU from the star. Right: Dependence of the evolution at different distances from the star for objects with a fixed initial radius of $10^3$ cm.
Figure 4. Effects of radial-drift on the evolution of objects in the disc. Left: Comparison between the time evolution of objects in the disc with and without radial-drift, starting from $a_0 = 1$ AU. Continuous lines represents the isolated effects of ablation and the dashed lines show the combined effects of ablation and radial-drift. Right: The radial-drift of different-size objects in the disc. We excluded any other process besides radial-drift and cutoff the evolution at a minimal distance of 0.1 AU from the star.

where $v_r$ is the radial component of the relative-velocity.

Fast radial-drift, which peaks at $St \approx 1$ (decimetre to metre-size objects for distances of 1 AU), can enhance the ablation. Inspiral in the disc transfers objects to the inner regions of the disc, where the radial gas density increases and the ablation is more effective, as can be seen from Figures 4 and A1. Furthermore, ablation can reinforce the radial-drift. Large objects are less likely to be affected significantly by radial-drift, but ablation can curtail objects and impel them to sizes where radial-drift becomes more effective.

As can be seen from Figure 4 (and in Figure 2 as well), at 5 AU ablation by itself is an inefficient process, little affecting objects of $\sim 10^3$ cm radii. However, radial-drift enables objects to inspiral closer to the star and reach the denser environments where ablation becomes significantly faster.

Turbulence in discs can change the relative-velocity of objects and hence affect on the nature of ablation, even in the absence of any radial-drift (e.g. in migration traps). In order to study the importance of turbulent velocities for ablation, let us parametrise the strength of turbulence in the disc using a simplified Shakura-Sunyaev $\alpha$ approach describing the effective kinematic viscosity, here taken to be $\alpha = 0.01$ and constant during the evolution. The effective kinematic viscosity of the turbulent gas is then given by Shakura & Sunyaev (1973), $\nu = \alpha c_s H_g$, where $H_g = a (c_s/v_k)$ is the scale height of the gas. The turbulent velocity of the largest scale eddies is $v_t = \sqrt{\alpha c_s}$. The turbulence adds a nonzero root-mean-square velocity, i.e. $v = v_{\text{rad}} + v_{\text{turb}}$. For large Stokes numbers, the addition can be modeled by $N \sim St$ uncorrelated velocity kicks from the largest scale eddies that generate a random-walk in velocity and the addition of $v_{\text{turb}} \sim v_t/\sqrt{St}$. For small Stokes numbers, the velocity addition scales as $v_{\text{turb}} \sim v_t$. The expression $v_{\text{turb}} = v_t/\sqrt{1 + St}$ can represent the behavior of the additive velocity in both these regimes (see Rosenthal et al. 2018 for details).

The influence of the turbulent velocity therefore depends strongly on the Stokes number of the object, and is given by

$$v_{\text{rad}}/v_{\text{turb}} = \eta St \frac{\sqrt{(1 + St)(4 + St^2)}}{1 + St^2}$$

For small objects, or equivalently, small Stokes numbers, the gas-pressure induced relative velocity dominates over the turbulent-induced velocities; and for large objects, the turbulent velocities dominate.
Figure 5 shows the contribution of turbulent velocities to evolution of objects in discs. Given the expected high turbulent velocities ($\sim 10^4 \text{ cm/sec}$) in comparison to ‘bare’ relative velocities ($\sim 10^2 \text{ cm/sec}$), it becomes evident that turbulence could play an important role in the enhancement of ablation processes. The timescales of turbulence-enhanced ablation are shorter, and metre-size objects can be eroded to decimetre-size objects in less than $10^3 \text{ years}$. In particular, migration traps suggested to potentially resolve the "metre-size" radial-drift barrier for planet formation give rise to a far stronger "metre-size" ablation barrier in this case.

4 DISCUSSION AND SUMMARY

In this paper we discussed the ablation barrier in planet formation. Ablation efficiently erodes boulders of size $\lesssim 50 \text{ m}$ up to $\sim \text{ cm}$ sized scaled at 1 AU (and larger boulders in the inner disc), thus it poses a barriers beyond the metre size. As a consequence, an initial planetesimal population much larger than $50 \text{ m}$ is required, either produced in-situ in the disk or captured from the interstellar medium through planetesimal seeding at the protoplanetary disc stage (Grishin et al. 2019).

Moreover, ablation operates even under conditions a priori more favorable to planetesimal growth such as migration-traps, if the disc is turbulent. Ablation significantly affects the evolution of small bodies and their size distribution and therefore has important implications for the evolution of protoplanetary-discs and their constituent dust-aggregates, pebbles and planetesimals.

Another aspect of ablation in discs is its contribution to growth via pebble-accretion. As we showed before (in Figure 2), ablation has a characteristic size range in which it operates efficiently and erodes planetesimals into pebble-size, which are then relatively unaffected by ablation. Henceforth, ablation can assist the growth of planetary embryos at later stages through the provision of small pebbles, which are more efficiently accreted on the embryos.

Potential caveat could be the validity of the ablation formula for low velocities. In our context the ablation is a much slower process than traditionally considered. Laboratory experiments have shown that a critical pressure of the gas flow is required to effectively erode dust aggregates (Paraskov et al. 2006; Demirci et al. 2019; Shao & Lu 2000). However, the experiments were conducted under room-temperature, and examined small cubical structures, which results were then scaled to larger size planetesimals, but the scaling chosen might not be appropriate for realistic planetesimals (linear scaling with size rather than quadratic scaling as expected from surface impact).

We have considered the effects of ablation on circular orbits. Even a small eccentricity, $e > c_1/v_0 = 0.022$ could lead to large, supersonic relative velocities, which in turn makes ablation much more efficient. However, gas drag would rapidly quench any significant eccentricity for planetesimals strongly coupled to the gas. One possibility for long-term eccentric evolution might be the case where some process keeps the bodies eccentric for a long amount of time (e.g. resonances, circumbinary disks and/or external perturbations), the subsequent ablation in such cases could be much more efficient. The relative velocity could also be altered if binary planetesimals are present (Perets 2011; Grishin & Perets 2016). Finally, similar processes of planetesimal ablation could be important for planetesimals in scaled-down discs, such as circumplanetary discs (Fujita et al. 2013) or discs around white dwarfs (Grishin & Veras 2019).

A possible extension of our study would be to consider different initial shapes of objects and the effect of ablation on them – it might carve them into more aerodynamic shapes. Ablation might then explain the unique shape of interstellar objects such as ‘Oumuamua (1I/2017 U1) (Meech et al. 2017) and Borisov (C/2019 Q4).

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APPENDIX A: DEPENDENCE ON DISC PARAMETRES

In the following we consider the dependence of ablation efficiency on the properties of the protoplanetary-disc. In Figure A1, we present these dependencies.

It can be seen that ablation is more significant for lower disc temperatures, higher gas densities and higher gas-pressure support parameters. Denser gas enables more interactions that potentially induce ablation, lower temperature changes the speed of sound and hence the Reynolds number and the gas-pressure support change the relative velocity.

APPENDIX B: DEPENDENCE ON MATERIAL/COMPOSITION

Different materials are expected to show different sensitivity to ablation processes. On the one hand, higher densities are expected to experience less intensive ablation, since the rate is proportional to \( \frac{1}{\rho p} \); on the other hand, the latent heat might compensate it. Moreover, the Stokes number is affected from the density as well, and hence the regime of coupled radii is different – denser objects decouple from the gas in smaller sizes, and henceforth effectively behave as larger objects.

Figure B1 presents a strong dependence of the ablation rate on the material of the object.

APPENDIX C: DEPENDENCE ON TURBULENT VELOCITIES

Different turbulent velocities, which arise from different viscosities, can change the ablation rate. As can be seen from Figure C1, higher values of Shakura-Sunyaev constant, i.e. \( \alpha \), lead to more significant effect of ablation.

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Figure A1. Time evolution of metre-size objects at a fixed distance of 1AU from the star. Figure (a) shows the dependence on temperature. Figure (b) shows the dependence on the overall central density. Figure (c) shows the dependence on the gas-pressure support parameters.

Table C1. Supplementary parameters

| Symbol | Definition | Expression | Reference |
|--------|------------|------------|-----------|
| Q      | latent heat | \(8.08 \times 10^8 \frac{m}{g}\) | Pollack et al. (1996) |
| \(C_h\) | heat transfer coefficient | 0.1 | Valletta & Helled (2018); Podolak et al. (1988) |
| \(\rho_g\) | radial gas density | \(3 \times 10^{-9} \frac{(a/\text{AU})^{-16/7}}{\text{cm}^3}\) | Perets & Murray-Clay (2011) |
| \(\rho_p\) | planetesimal\'s density | \(3.45 \times 10^{-10} \frac{g}{\text{cm}^3}\) | Pollack et al. (1996) |
| \(\eta\) | gas-pressure support parameter | \(10^{-3} \frac{g}{\text{cm}^2} a^{14/7}\) | Grishin & Perets (2015) |
| \(St\) | Stokes number | \(\Omega_{\text{stop}} \frac{4 R_v}{v_{\text{th}} a}\) | Perets & Murray-Clay (2011); Armitage (2010) |
| \(Re\) | Reynolds number | \(\frac{v_{\text{th}} a}{v_{\text{th}} a}\) | Perets & Murray-Clay (2011) |
| \(v_{\text{th}}\) | thermal velocity | \(\sqrt{\frac{8 \pi c_s}{\mu}}\) | Perets & Murray-Clay (2011) |
| \(c_s\) | speed of sound | \(3.93 \times 10^{-2} \frac{g}{\text{cm}}\) | Rosenthal et al. (2018) |
| \(\mu\) | mean molecular weight | \(1.4 \times 10^{-22} \frac{g}{\text{cm}^3}\) | Perets & Murray-Clay (2011) |
| \(\lambda\) | mean-free path | \(10^{-15} \text{cm}\) | Perets & Murray-Clay (2011) |
| \(n_g\) | gas number density | \(10^{-15} \frac{g}{\text{cm}^3}\) | Perets & Murray-Clay (2011) |
| \(\sigma\) | neutral collision cross-section | \(120 \frac{\Omega}{\Omega_{\text{stop}}} a^{-3/7}\) | Perets & Murray-Clay (2011) |
| \(T\) | temperature | \(120 \frac{\Omega}{\Omega_{\text{stop}}} a^{-3/7}\) | Rosenthal et al. (2018) |
| \(\alpha\) | Shakura-Sunyaev constant | \(10^{-2}\) | Rosenthal et al. (2018) |

Figure B1. The dependence of ablation on the material, for metre-size objects at a fixed a of 1AU distance from the star.

Figure C1. The dependence of ablation on turbulent velocities, for metre-size objects at a fixed a of 1AU distance from the star. We added an artificial lower-cutoff at a radius of 1 cm.