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SELF-INDUCED DUST TRAPS AROUND SNOWLINES IN PROTOPLANETARY DISCS

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Abstract. In the core accretion paradigm of planet formation, dust particles need to grow efficiently from micrometer sizes to thousands of kilometers. While the first stages are well understood, the growth through intermediate (mm to km) sizes is hindered by a number of barriers. While many solutions have been proposed, the recent discovery of self-induced dust traps has provided a natural and independent solution to overcome those barriers, opening the way to further investigations towards planetesimal formation. Another natural mechanism present in discs, is the condensation and sublimation of volatile species at certain locations, called snowlines. They separate regions with different grain sticking properties, because of the presence, or absence, of an ice mantle. The Carbon Monoxyde (CO) snowline has been detected in different protoplanetary discs, which raises the question: how do they affect the promising self-induced dust trap formation mechanism ? In this paper, we address this question and present the effect of snow lines on self-induced dust trap formation in a parameter study. We find that for a large number of configurations, a dust trap forms at the snow line location where the dust piles up and slowly grows. We also suggest that planetesimal formation can start at or from the CO snowline. This could provide a link between dust structures and snow lines locations in future disc observations.

Keywords: Protoplanetary discs - Hydrodynamics - Planets and satellites: formation - Methods: numerical

1 Introduction

Currently, one of the main scenarios for planet formation is the core accretion model, i.e. planets are the results of the dust slowly growing to larger sizes through coagulation (Hartmann et al. 1998). Unfortunately, it struggles explaining how mm to m dust grains are able to survive in the disc for two reasons.
1. Since the gas is sensitive to its own pressure gradient, it orbits the star slightly slower than the dust. As a result, the dust feels a headwind and lose angular momentum, which makes it drift towards the star. Intermediate (mm to m) size grains are the ones that are the most affected and drift the fastest (Weidenschilling 1977). This results in their accretion and is called the radial drift barrier (Laibe et al. 2012).
2. When grains drift to the inner part of the disc, their relative velocity increases due to the increase in temperature. This means that at a certain point, the grains shatter rather than grow, which prevents them from slowing down their drift and reaching larger sizes. This is called the fragmentation barrier (Blum & Wurm 2008).
To solve these problems, one can trap dust into pressure maxima, thus stopping its drift (Haghighipour 2005). A few mechanisms have been proposed to create such maxima. While the majority depends on specific conditions, Gonzalez et al. (2017) showed that the back-reaction of the dust onto the gas naturally leads to the formation of a pressure maximum created by the dust evolution. They called it self-induced dust trap. In this study, we focused on those self-induced dust traps and particularly on snow lines, because they also do not require *ad hoc* conditions and are naturally present in discs. Snow lines are the condensation (or sublimation) fronts of volatile species and have been observed (mainly for Carbon Monoxyde (CO)) recently (Qi et al. 2015; Macías et al. 2017). When some volatile species is freezing out at the surface of grains, it changes their sticking properties, thus affecting the way they grow, fragment and by extension drift. This should modify the self-induced dust trap formation scenario and this the investigation we conducted in this study.

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2 Methods

2.1 Numerical simulations

To simulate protoplanetary disc evolution, we use our 3D, two-phase (gas+dust), Smoothed Particles Hydrodynamics (SPH) code (Barrière-Fouchet et al. 2005). Gas-dust aerodynamic coupling is incorporated taking into account the back-reaction of the dust onto the gas. We simulate a typical disc, called "Steep" model that represents an "averaged" observed disc. The disc and our numerical setup are identical to the ones in Gonzalez et al. (2017) and we refer the reader to it for further information.

2.2 Growth and Fragmentation models

The implementation of grain growth is that of Laibe et al. (2008) meanwhile fragmentation is that of Gonzalez et al. (2015). The turbulent relative motion between grains allows them to grow (Stepinski & Valageas 1997) if their relative velocity is lower than a fragmentation threshold, noted $V_{\rm frag}$. The dust growth rate is either positive (i.e. if $V_{\rm rel} < V_{\rm frag}$) or negative (i.e. if $V_{\rm rel} > V_{\rm frag}$) and follows the prescription:

$$\frac{\mathrm{d}s}{\mathrm{d}t} = \pm \frac{\rho_{\rm d}}{\rho_{\rm s}} V_{\rm rel}, \tag{2.1}$$

where $V_{\rm rel}$ is the relative velocity between dust particles while $\rho_{\rm d}$ and $\rho_{\rm s}$ are the volume density of the dust phase and the intrinsic density of the dust material, respectively.

2.3 Snow lines as discontinuities in fragmentation threshold

We incorporate in our simulations a snow line. To represent its effect we adopt different values of the fragmentation velocity such that $V_{\rm fragin}$ corresponds to the inner fragmentation threshold and $V_{\rm fragout}$ to the outer one. This change in $V_{\rm frag}$ mimics the change in grain surface composition, meaning that the smaller the fragmentation threshold is, the weaker the corresponding grain will be regarding fragmentation. We define the position of the snow line $r_{\rm snow}$ either as the location where the temperature is equal to the sublimation temperature $T_{\rm subl}$ or arbitrarily. By sweeping-up the parameter space ($V_{\rm fragin}$, $V_{\rm fragout}$ and $r_{\rm snow}$), we investigate the role snow lines play in the formation of self-induced dust traps.

3 Results

3.1 The snow line position

First, we fix the fragmentation threshold to 15 $\mathrm{m\,s^{-1}}$ in the outer disc and 5 $\mathrm{m\,s^{-1}}$ in the inner disc, thus representing a significant decrease in the ability to stick for the grains inside of the snow line. In Fig. 1 we show the final snapshot of 3 simulations hosting snow lines at 50, 100 and 150 AU, representing relatively close, intermediate and far cases. The right panel shows dust grains remaining at small sizes, due to the fact that dust growth is hindered very early in its history because grains reach a zone where the fragmentation velocity is very low far from the star. As a result, grains cannot grow and drift efficiently and fail to gather enough material to decouple from the gas. Meanwhile, the left and middle panels show remarquable correlation between their dust pile up and the snow lines locations. We see that the dust is more concentrated for the closest snow line (50 AU) than for the intermediate distance one (100 AU). This is because the dust pile-up tends to happen between 80 and 90 AU, where the grains would naturally cross St $\sim$ 1 and therefore slow down their drift.
The left panel of figure 1 is really interesting because it gives a link between the dust distribution and the snow line position. This is why we decided to investigate more closely for snow lines a bit closer to the star. In Fig. 2 is presented this investigation with snow lines at 30 (top), 40 (middle) and 50 (bottom) AU. We also show the gas pressure profile for those simulations, and we cannot help but see a very clear dust pile-up located at the snow line, everytime. The more close in the snow line is, the denser the trap has become which translates into higher gas pressure bumps and bigger grains.

3.2 The Carbon Monoxyde (CO) snowline

The position of the snow line being a key parameter to understand how it affects the dust dynamics, the discontinuity also plays a major role in the evolution of self-induced dust traps at the proximity of snow lines. To

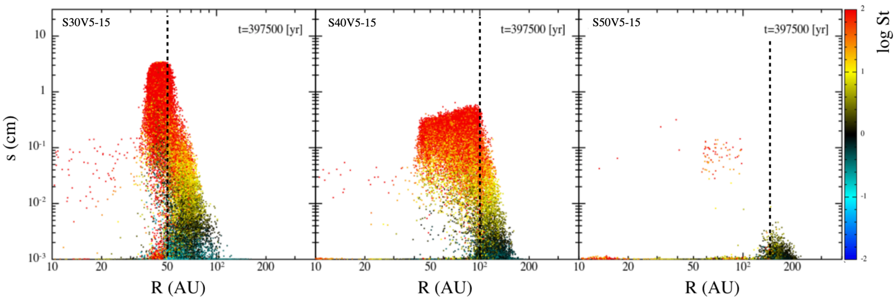

Fig. 1. Dust size as a function of their radial distance to the star for 3 simulations hosting a snow line at 50 (left), 100 (middle) and 150 (right) AU after 400,000 yr. For these simulations, the fragmentation thresholds are set to 5 ($V_{\rm fragin}$) and 15 ($V_{\rm fragout}$) m.s^{-1}. The grains are coloured with the Stokes number. The snow line is highlighted with a black dashed line on every panel.

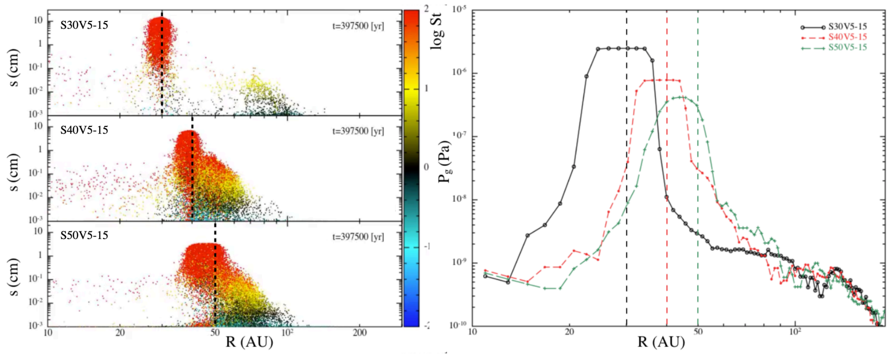

Fig. 2. Left: Dust size as a function of their radial distance to the star for 3 simulations hosting a snow line at 30 (top), 40 (middle) and 50 (bottom) AU after 400,000 yr. For these simulations, the fragmentation thresholds are set to 5 ($V_{\rm fragin}$) and 15 ($V_{\rm fragout}$) m.s^{-1}. The grains are coloured with the Stokes number. The snow line is highlighted with a black dashed line on every panel. **Right:** Gas pressure profiles for the same simulations.

understand it, we focus in this section on the physical CO snow line, which has been observed several times in recent papers (see references in Section 1).

The behaviour of CO ice is uncertain due to a lack of experimental data. While Pinilla et al. (2017) consider CO being weak with respect to fragmentation by adopting a fragmentation threshold similar to that of bare silicate grains (1 m.s^{-1}), we chose to consider multiples options. These are shown in Fig. 3. For our disc, the snow line position was evaluated by equating the CO sublimation temperature (20 K) to the disc temperature, which gives $\sim$ 100 AU. The first four panels model a stronger CO ice mantle with respect to fragmentation meanwhile the last two try the opposite.

The first 3 panels show, as we have seen in Section 3.1, a dust pile-up at the snow line location. The ability for the snow line to stop the dust drift is more and more challenged as the discontinuity (i.e. the ratio between the fragmentation thresholds) comes close to 1. As a result, the fourth panel shows that the dust traps forms inside of the snow line, even though its width seems to extend up to $r_{\rm snow}$. For the last two panels, we do not see any correlation whatsoever between the dust and the CO snow line, even though at earlier stages we see the dust starting its growth from $r_{\rm snow}$.

To translate these cases into images, we used the radiative transfer code MCFOST (Pinte et al. 2006) to produce face-on synthetic views (Fig. 4. The 1-15, 3-15, 5-15 and 10-15 cases have very different signatures (e.g the width of the dust ring) while the last two are somewhat similar at that stage, but again not at earlier stages. While this is preliminary, we could use synthetic images to constraint the CO's effect on grains and its implication for planet formation and Carbon/Oxygen rich grains delivery to the inner part of the disc.

4 Conclusions

Taking into account the effects of snow lines on dust growth is a step towards a better understanding of planet formation. We showed that snow lines affect the dust dynamics through their growth and fragmentation and that it can lead to an efficient self-induced dust trapping at a remarkable location. The increasing number of CO snow line observations in the last few years paves the way to understanding its role in planet formation. Our

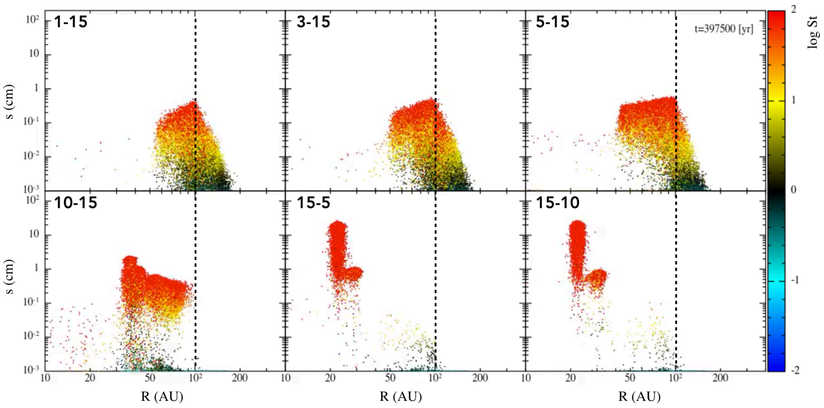

Fig. 3. Dust size as a function of their radial distance to the star after 400,000 yr for 6 simulations hosting a snow line at 100 AU representing the CO snow line. The grains are coloured with the Stokes number and the snow line is highlighted with a black dashed line on every panel.

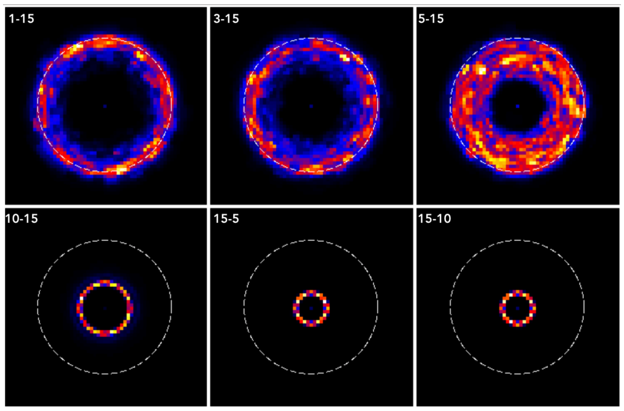

Fig. 4. Face on synthetic images at the end of the simulations shown in Fig. 3 with the nomenclature for the fragmentation thresholds on the top left of each panels. The snow line is represented by the white dashed circle on every panel.

simulations clearly show two possibilities: either dust growth happens at the snow line, or from its surroundings. To better compare these results to observations, we will use in a forthcoming paper the Atacama Large Millimetre Array (ALMA) utility CASA to give observers constraints on what to expect from the CO snow line and the dust structures.

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