EPSC Abstracts
Vol. 13, EPSC-DPS2019-1936-2, 2019
EPSC-DPS Joint Meeting 2019

EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

Icy pebble growth by nucleation and deposition at ice lines in protoplanetary discs

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Abstract

Outside of ice lines in protoplanetary discs particles can grow by direct vapour deposition. However, this growth may be hindered by the large amount of dust grains present in the disc. Experiments on heterogeneous ice nucleation show that a substantially higher water vapour pressure is required for the nucleation of a new ice surface than for continued deposition of vapour on an icy surface. We model icy particle growth in a dynamical 1D deposition and sublimation model, including radial drift, sedimentation and diffusion in a turbulent protoplanetary disc. We find that the water vapour pressure outside the ice line is too low for heterogenous ice nucleation to take place, and vapour is therefore deposited predominantly onto already icy grains. This results in a bimodal particle distribution, with centimetre-sized icy pebbles just outside the ice line and bare dust grains diffusing out over the disc.

1 Introduction

The water ice line have since a long time been thought of as a location in the disc where particle growth, and thereby planet formation, can be enhanced due to the large amount of water vapour taking solid form here [6, 1]. Deposition of water vapour onto solid grains has been found to increase particle sizes from millimetres up to at least centimetre-sizes in numerical models of deposition and sublimation at the water ice line [4, 5], thus facilitating growth towards planetesimals and planets here [2]. This pebble-growth may however be hindered by the inclusion of the large amount of small dust grains present in the disc, as these dust grains typically dominate the surface area. The majority of water vapour would then cause a negligible individual growth of a huge number of dust grains, instead of letting a fraction of the particles grow to pebble sizes. However, new experimental results performed in the context of the Martian atmosphere demonstrates that the onset of heterogeneous nucleation, or the formation of the first ice layer on a dust particle, requires a substantially higher water vapour pressure than the deposition of vapour on an already icy surface [3]. We find that including this distinction between heterogeneous ice nucleation and vapour deposition when modelling particle growth due to sublimation and deposition leads to a suppression of ice growth on bare dust grains, and allows icy pebble growth to proceed to centimetre-sizes.

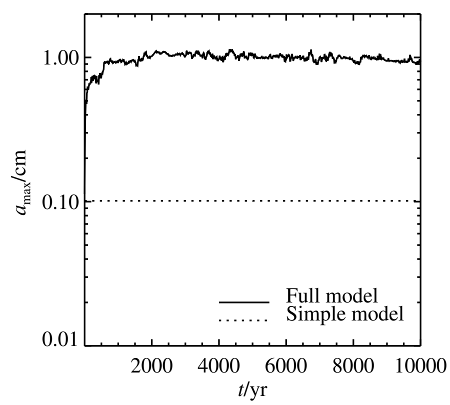

Figure 1: Maximum particle size as a function of time for the full temperature-dependent nucleation model (full line) and a simplified model (dotted line) where the distinction between forming the first ice layer and continued deposition is not included. In the full model the initially millimetre-sized particles grows to centimetre-sized pebbles, whereas in the simple model vapour is instead deposited on the micron-sized dust grains.

2 Model

We develop and run a dynamical model of the growth of micron-sized and millimetre-sized silicate dust particles due to heterogenous ice nucleation and depostion of water vapour, including the release of water vapour and silicate nuclei upon sublimation. Our model is set in a one-dimensional local region around the water ice line, at $r \approx 2.6\,\mathrm{au}$, in a turbulent protoplanetary disc, including radial drift, turbulent diffusion and sedimentation. Particle collisions are not included.

3 Results

In Figure 1 we show particle growth as a function of time for our full temperature-dependent nucleation model, and compare it to a simplified model where we ignore the difference between heterogenous ice nucleation and vapour deposition. In our full nucleation model, the formation of a new ice layer on dust particles is not possible. Thus, when an icy particle drifts across the ice line and loses its ice mantle it can no longer grow by deposition and the available vapour can only be deposited on the remaining icy particles. In the simplified model, small dust grains that represent the majority of the available surface area, shares most of the available vapour, and thereby growth to large particle sizes is inhibited.

4 Conclusions

We find that the suppression of heterogeneous ice nucleation leads to a bimodal size distribution, where icy particles can grow to centimetre-sizes in $t \approx 1000\,\mathrm{yr}$ and bare dust grains do not grow but instead diffuse out over the disc. The suppression of heterogenous ice nucleation thus enhances particle growth and is in agreement with models showing that the ice line can be a preferential site for planetesimal and planet formation.

References

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