

Pebble formation by ice condensation

Katrin Ros^{1,a}

¹*Lund Observatory, Department of Astronomy and Theoretical Physics, Lund University, Box 43, 221 00 Lund, Sweden*

Abstract. Pebbles with sizes of centimeters to decimeters are needed in order to form kilometer-sized planetesimals, which in turn are needed for planet formation to proceed. The well-studied mechanism of coagulation is efficient only up to millimeter-sized dust grains. In this proceeding a numerical model of ice condensation as a complementary growth mechanism in turbulent protoplanetary discs is discussed. Close to an ice line, particles grow efficiently by ice condensation, which, combined with radial mixing, can supply a large extent of the disc with icy pebbles. Growth from millimeter-sized dust grains to at least decimeter-sized pebbles is possible on a time scale of only 10 000 years. The resulting particles are large enough to enable further growth into planetesimals via a variety of particle concentration mechanisms and subsequent gravitational collapse.

1 Introduction

A crucial step towards forming planets is the formation of planetesimals, kilometer-sized rocky and/or icy bodies, in protoplanetary discs. Growth from pebbles larger than a few centimeters up to kilometer-sized planetesimals is possible by clumping of particles, followed by gravitational collapse. Such particle concentration events can occur by a number of different mechanisms; via streaming instabilities [1, 2], in long-lived vortices [3–5] and in pressure bumps [6]. However, in order to form planetesimals via any of the aforementioned paths pebbles of several centimeters in size are needed. The most well-studied growth mechanism for small particles, coagulation, is efficient only up to millimeter-sizes [7, 8]. There is thus a gap between millimeter-sized dust grains and pebbles of several centimeters, where particles are too large to grow by coagulation, but too small to be sensitive to any known particle concentration mechanism. An efficient path for growth from dust grains to pebbles is therefore needed in order to enable further growth into planetesimals via clumping and gravitational collapse.

Ice condensation is a growth mechanism with the potential to bridge this gap [9, 10]. In a turbulent disc, small particles close to an ice line diffuse into the hot regions close to the central star and in the disc atmosphere and sublimate. Vapour diffusing back across the ice line into the condensation region condenses onto already existing particles, leading to significant growth. This proceeding is based on work presented in [11], where we studied the dynamical behaviour and growth of small (~ 1 mm) seed particles via ice condensation in computer simulations. We considered diffusion across both the

^ae-mail: katrin.ros@astro.lu.se

radial ice line, separating the cold outer region from the hot inner part of the disc, and the *atmospheric ice line* separating the cold disc midplane from the hot disc atmosphere [12–14].

In this proceeding, focus is on the water ice line at around 3 AU [15]. However, it is important to remember that particle growth by condensation is relevant at any condensation front in the protoplanetary disc, such as those of carbon monoxide and molecular nitrogen further out in the disc, and those of silicates close to the central star [16, 17].

2 Method

The simulation domain is a two-dimensional local region around the water ice line, where the radial r and vertical z directions are taken into account. Since a typical particle size resulting from coagulation is millimeters, the initial seed particle size is set to 1 mm.

Small ($a \lesssim 1$ cm) particles are coupled to the turbulent gas via drag forces, and the resulting particle motion is modelled as a random walk. Larger particles decouple from the gas and becomes more susceptible to the gravity towards the midplane. In the vertical direction the particle scale height for any particle size is thus set by an equilibrium between turbulent diffusion and sedimentation towards the midplane [18, 19]. In the radial direction the headwind from the pressure-supported gas causes particles to drift towards the star [20]. These dynamical effects are all implemented in the model used for the simulations presented here.

A short sublimation time scale motivates modelling of sublimation as an instantaneous process, where an ice particle drifting across the ice line sublimates within one orbital period. Condensation is modelled as a neighbour interaction, where at least one ice particle is required in the neighbourhood of a vapour particle in order for condensation to be possible. A Monte Carlo scheme is used, in which the probability of condensation for each vapour particle is proportional to the size of the available ice surface. The ice and vapour components are modelled using a superparticle approach, where a superparticle is a numerical representation of a large number of particles with identical properties, since the number of physical particles is too large to easily handle computationally [21].

3 Results

Starting from millimeter-sized seed particles, the size typically resulting from coagulation, centimeter-sized to decimeter-sized pebbles form via condensation within a few hundred orbits. Fig. 1 shows the state of the simulation at different times; at $t = 0$, $t = 100 \Omega^{-1}$ and at $t = 1000 \Omega^{-1}$, from top to bottom. Grey marks the cold condensation region and white is the hotter sublimation region. Vapour and ice particles are represented by red and blue filled circles, respectively, where the size of each blue circle is proportional to the size of the ice particle. The vertical distribution of both vapour and small ice particles follows the stratified gas, with the larger particles sedimenting towards the midplane. Sedimentation effectively aids the particle growth, since the larger the pebbles grow, the more unlikely they are to move into the hot disc atmosphere and sublimate.

In the middle panel it can be seen that the most efficient particle growth takes place close to the radial ice line. The main supply of water vapour thus comes from diffusion across the radial ice line, whereas the contribution of diffusion over the atmospheric ice line is significantly smaller. However, in a turbulent protoplanetary disc radial mixing is efficient enough to distribute the large pebbles over a vast radial extent. In this simulation a turbulent α -value of 10^{-2} is used. As can be seen in the lower panel of Fig. 1 this is sufficient for giving centimeter-sized to decimeter-sized pebbles throughout the entire simulation domain after only $\sim 1000 \Omega^{-1}$.

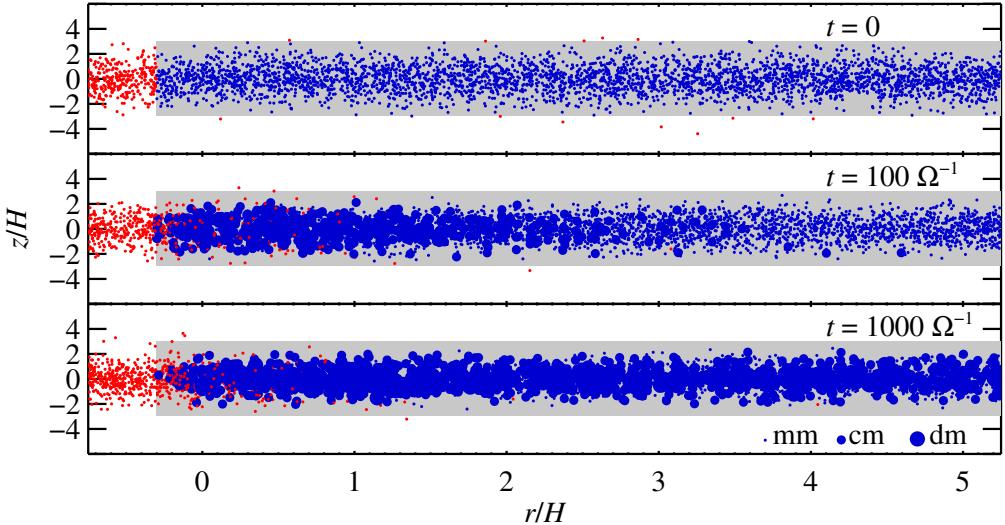


Figure 1. Snapshots of a simulation of a turbulent ($\alpha = 10^{-2}$) disc at $t = 0$, $t = 100 \Omega^{-1}$ and $t = 1000 \Omega^{-1}$, from top to bottom. The grey area represents the cold condensation zone, and ice and vapour are shown in blue and red, respectively. The sizes of the filled blue circles are proportional to the sizes of the ice particles and the number of particles shown is inversely scaled with size for visibility. The size of the simulation domain is given in terms of the gas scale height H . Particle growth is most efficient just outwards of the radial ice line, but due to radial mixing decimeter-sized pebbles are found throughout the entire condensation zone after only $1000 \Omega^{-1}$.

4 Discussion

Ice condensation is a mechanism with the potential to aid bridging the gap between dust grains, formed by coagulation, and the larger pebbles needed to enable further growth into planetesimals. In a turbulent protoplanetary disc, not only is significant particle growth by condensation possible close to an ice line, but the growing pebbles are efficiently transported to a large radial extent of the disc.

There are several issues requiring further investigation. Global models are needed in order to include the effects of ice lines other than that of water. Modelling ice particles as a refractory core with an icy mantle, as opposed to the simplified homogeneous ice particles in this work, could have an impact on the outcome. Collisions between particles also need to be taken into account. Including both coagulation and condensation in a global disc model will give a more realistic view of the implications of ice condensation on particle growth in protoplanetary discs.

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