Ice condensation as a planet formation mechanism

Katrin Ros & Anders Johansen
Lund Observatory
katrin.ros@astro.lu.se

Introduction

Context Planets form in protoplanetary discs of gas and dust surrounding young stars. This is thought to happen in a bottom-up-scenario, in which small dust grains collide, stick together and build larger and larger bodies, up to km-sized planetesimals and even larger planets.

The pebble formation problem Dust particles (<mm) stick together due to contact forces. Dm-sized pebbles grow towards planets via instabilities and gravitational collapse (Johansen et al., 2007). Growth from mm to dm has not yet been explained, as these particles tend to fragment when colliding (Blum & Wurm, 2008; Brauer et al., 2008), and are too small to induce dynamical instabilities.

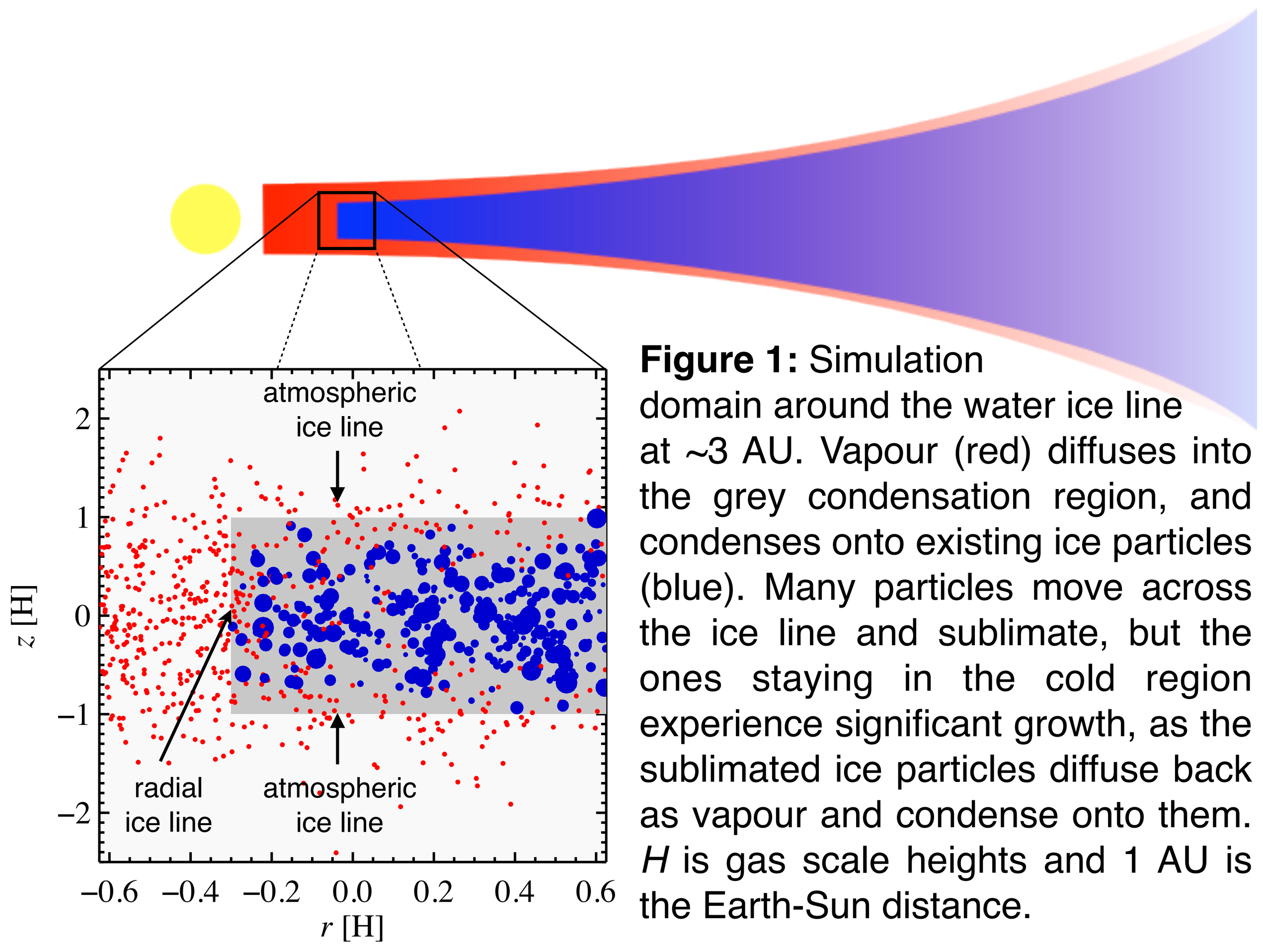

Figure 1: Simulation domain around the water ice line at ~3 AU. Vapour (red) diffuses into the grey condensation region, and condenses onto existing ice particles (blue). Many particles move across the ice line and sublimate, but the ones staying in the cold region experience significant growth, as the sublimated ice particles diffuse back as vapour and condense onto them. *H* is gas scale heights and 1 AU is the Earth-Sun distance.

Aim Pebbles are observed in protoplanetary discs (Wilner et al., 2005), and are a crucial step towards planets. We investigate their formation via ice condensation in a turbulent disc.

Condensation model The temperature gradient in a disc gives rise to condensation fronts, or ice lines, where volatiles, such as water, changes phase from vapour to ice. At an ice line, volatiles diffusing into the colder region condense onto existing particles, causing significant growth (Stevenson & Lunine, 1988).

Figure 1 shows the simulation domain schematically in a crossectional sideview of a protoplanetary disc.

Dynamics

Vertical structure: diffusion - sedimentation Water vapour and small ice particles are coupled via drag forces to the turbulent gas in the disc. The resulting turbulent diffusion can be modelled as a random walk.
The vertical component of the stellar gravity causes sedimentation towards the midplane, an effect which increases with larger particle sizes.

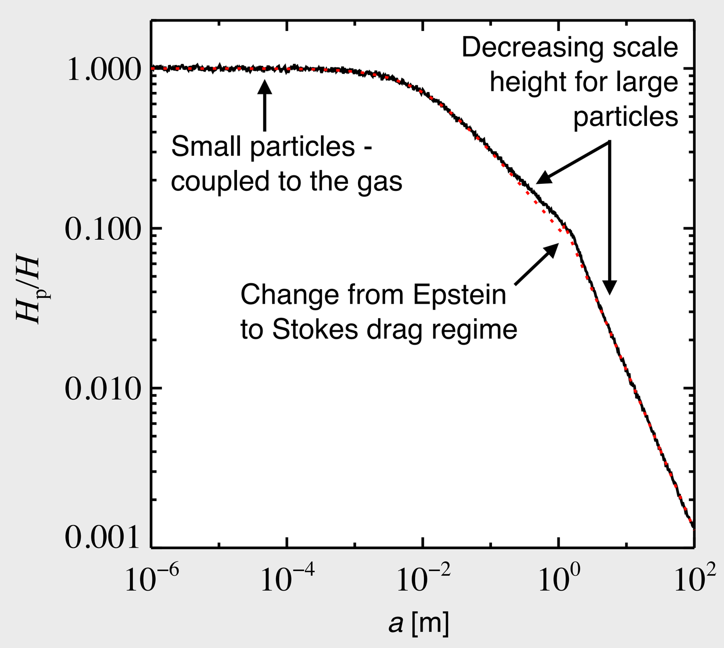

Figure 2: Particles settle to an equilibrium between diffusion and sedimentation. The full black line denotes modelled values and the dotted red line corresponds to analytical values, assuming diffusion-sedimentation equilibrium. Small particles are strongly coupled to the gas, whereas larger particles sediment out to the midplane. The slope change at *a* ~1.7m is due to a change between different gas drag regimes.

Horizontal structure: diffusion - radial drift The disc is hotter and denser closer to the central star, giving a resulting outwards pressure gradient force that causes the gas to orbit slightly slower than Keplerian. Particles in orbit thus face a constant headwind, making them spiral in towards the central star. The radial drift is negligible for small particles, peaks for m-sized particles, and decreases for larger particle sizes.

Condensation

Condensation requires ice nuclei Unless significant supersaturation, vapour does not homogeneously nucleate, but needs existing ice or dust particles to condense onto.

Condensation is independent of particle radius The growth rate by condensation for one ice particle is given by

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{\rho_v v_{th}}{\rho_\bullet} .$$

ρ_v and v_{th} are the density and thermal velocity of vapour, and $\rho_\bullet$ is the material density of the ice particle.
In a certain time interval dt any two ice particles therefore grow with the same radius da. The larger one thus experience a larger mass increase during a time interval.

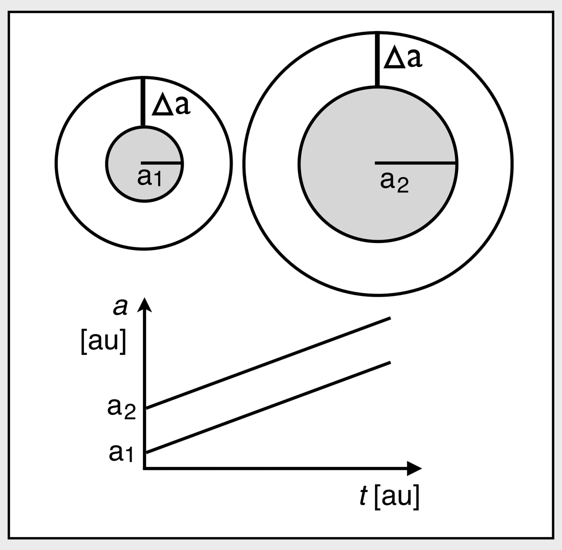

Figure 3: Linear growth rate

Modelling condensation We use a Monte Carlo scheme, where small particles are the preferred size for condensation, as they have the largest combined surface area in a given mass bin.

Modelling sublimation The short sublimation time scale motivates modelling of sublimation as an instantaneous phase change as the ice particle crosses the ice line.

Results

Particle growth to cm- or dm-sized pebbles on a time scale of 1000 years Starting from mm-sized ice particles, condensation of vapour onto existing ice particles leads to significant growth around the ice line.

Figure 4 shows the size evolution in time. Small ice particles grow quickly to cm-sizes and start sedimenting towards the midplane. Vapour is supplied both via the radial and the atmospheric ice lines. The resulting particles form a dense midplane layer with a narrow size distribution around dm-sizes.

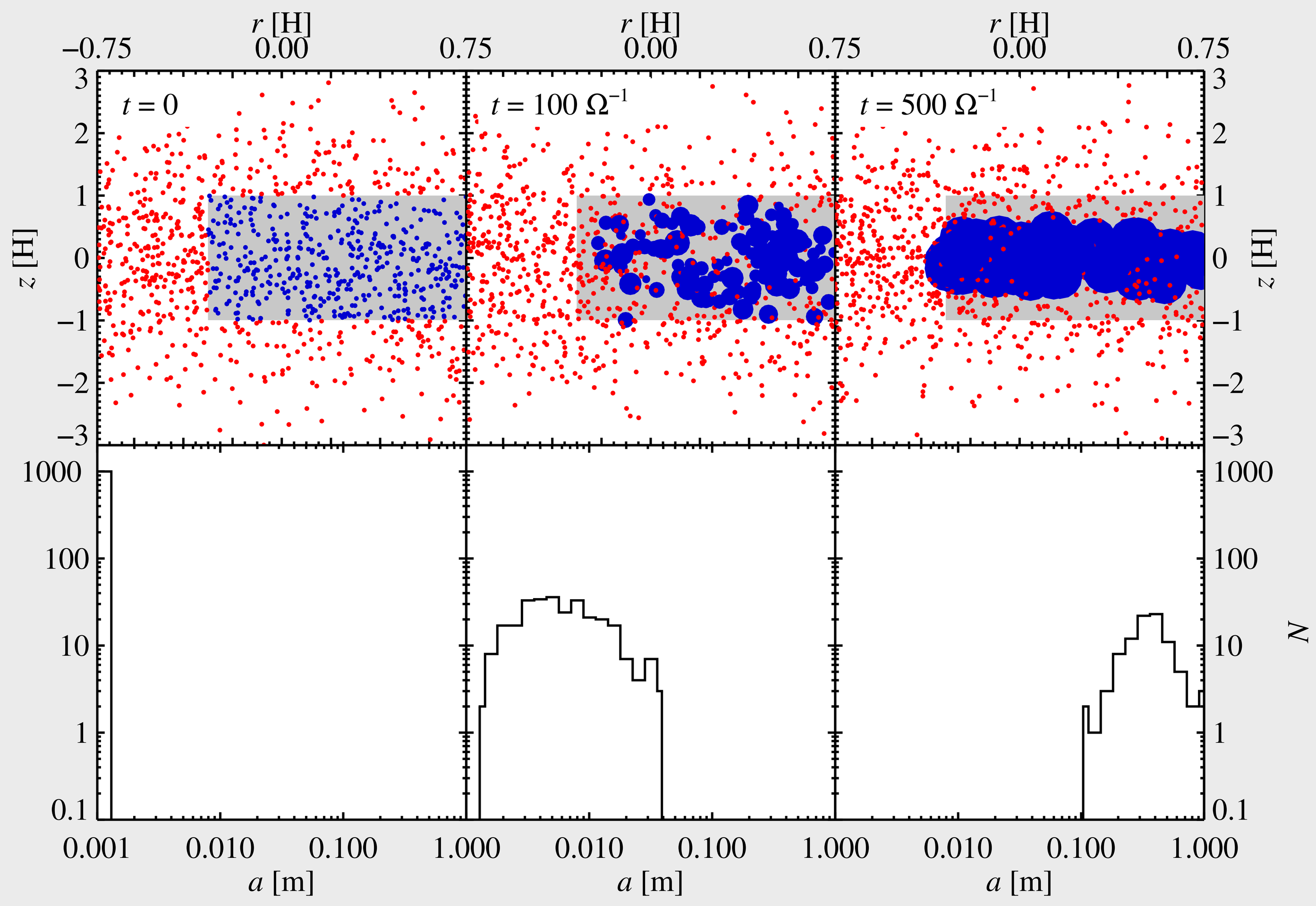

Figure 4: Particle distribution and size evolution in time. Blue represents ice particles and red vapour. The condensation region is marked in grey. The lower panels show the size distribution, with *N* being the number of particles. Time is shown in inverse Keplerian orbits, where $1\Omega^{-1} \sim 1$ year at 3 AU.

References
Blum & Wurm, 2008, ARA&A, 46, 21
Brauer et al., 2008, A&A, 480, 859
Johansen et al., 2007, Nature, 448, 1022
Stevenson & Lunine, 1988, Icarus, 75, 146
Wilner et al., 2005, ApJ, 626, L109

Conclusions

Ice condensation can solve the pebble formation problem Our results show that ice condensation can bridge the gap from mm to dm, making further growth towards planets possible.

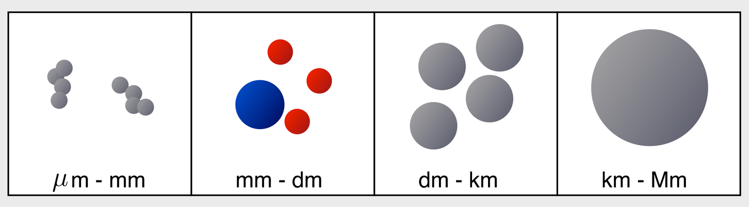

Figure 5: Schematic overview of planet formation from dust to planets. Dust grains grow by collisions. Growth from pebbles to planetesimals happens via dynamical instabilities and subsequent gravitational collapse, and graviational interactions explain the last step to planets. The gap between dust and pebbles is bridged by ice condensation, as shown in this work.