Gaps and rings at ice lines: Icy pebbles and small rocky dust

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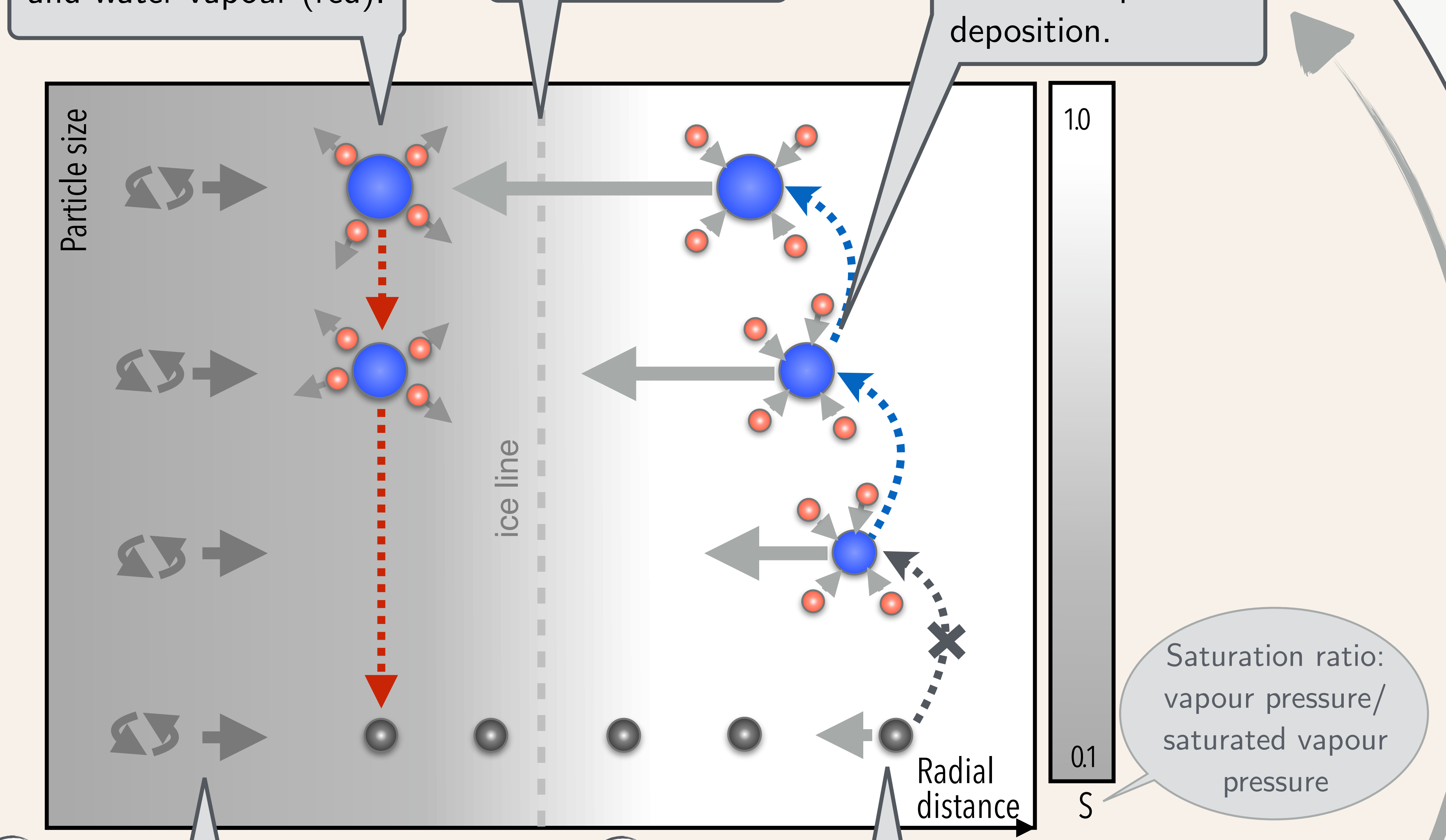
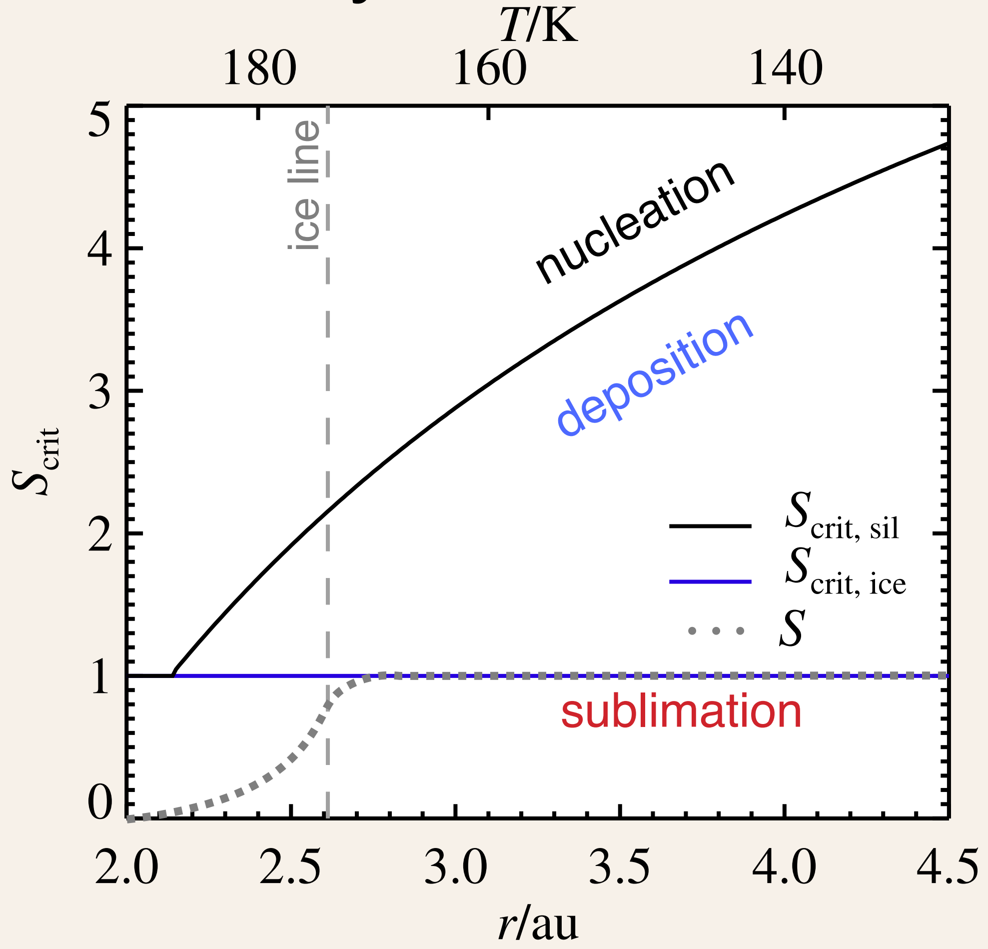
We modelled particle growth by condensation around the water ice line: The result is a bimodal size distribution with fast-growing icy pebbles locally at the ice line and small, rocky dust particles spreading out over the disc. This supports the idea of disc substructures forming at ice lines. Distinguishing between nucleation of ice on rock, and deposition of vapour on already ice particles, is the key to growth.

Sketch of the model

1. Icy particles (blue) grow when vapour (red) freeze out on them — vapour deposition.
2. Pebbles move across the ice line due to radial drift (grey left-pointing arrows).
3. Sublimation results in a silicate nucleus (black) and water vapour (red).
4. Turbulent diffusion (grey swirls with right-pointing arrows) spread vapour and small particles out over the disc.
5. Bare dust grains cannot get a new ice mantle (nucleation) since the vapour pressure at the ice line is too low. All vapour is instead deposited on icy particles as in (1.)

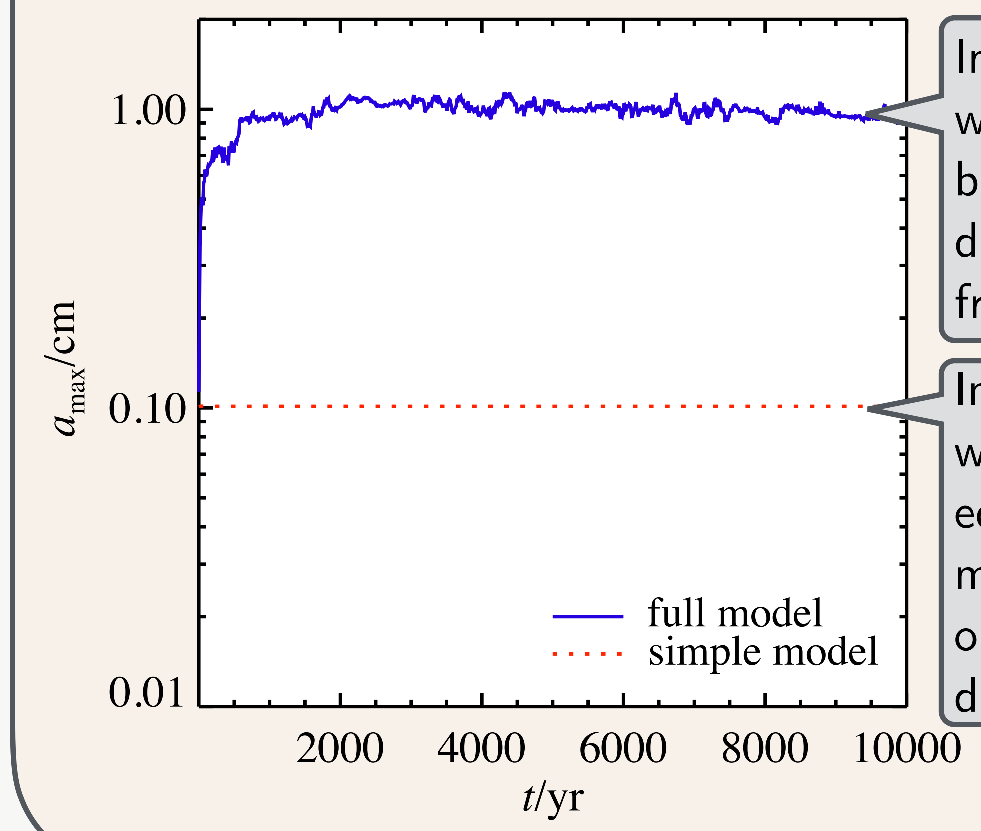


Key concept: Vapour can freeze out on icy particles, but not on bare rocky surfaces. Why?



Critical saturation ratio for deposition on ice $S_{crit,ice}$=1 (blue), and for nucleation on silicate $S_{crit,sil}$=-0.0626 T+13 (black), experimentally determined by Iraci et al (2010). The saturation ratio we find in our model is overlaid as a grey dotted line. This saturation ratio allows for sublimation and deposition, but never reaches high enough values for nucleation.

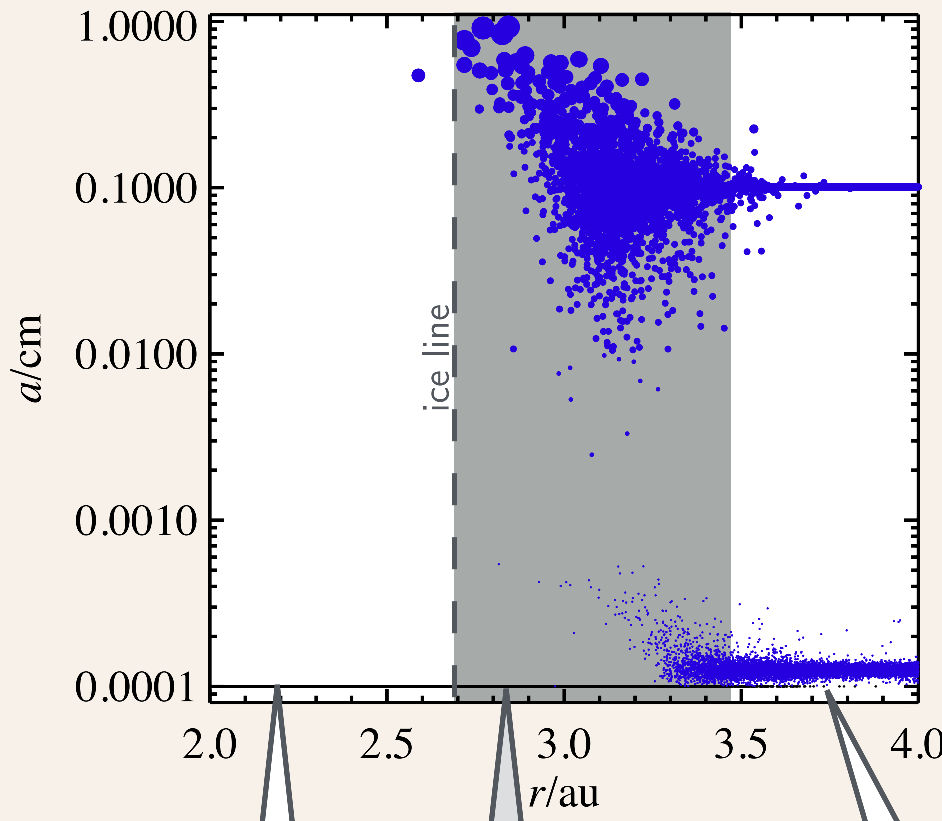
Result: The difference between nucleation and deposition is the key to growth



In our full model (blue) where we included the difference between nucleation and deposition icy particles grew from mm to cm.

In a simplified model (red) where vapour freezes out equally well on rock and ice most of the vapour condenses on small dust, and particles did not grow above mm.

Result: Icy fast-growing pebbles at the ice line, small rocky dust elsewhere



Starting from micron-sized and millimeter-sized particles, after 1000 years we find cm-sized icy pebbles at the ice line, while surrounding regions are dominated by small dust. Blue is ice-covered particles, black is bare, rocky particles. Collisions are not included in this model.

Sublimation region: small rocky dust.

Locally at the ice line: deposition-dominated growth to icy pebbles

No growth: small particles diffuse out over the disc