Towards understanding CO depletion in wind-driven discs

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ALMA observations show that CO is depleted in protoplanetary discs. CO depletion is thought to be driven by a combination of turbulent mixing, freeze-out and grain surface chemistry. BUT discs may be wind-driven with weak turbulence. How does CO depletion proceed in wind-driven discs?
This poster covers an initial exploration of the dust dynamics in wind-driven discs, and we are now working towards full simulations to model CO depletion.

CO is mixed down to midplane and depleted in warm disc layers above the ice line (black dashed line). → **Efficient ice formation traps CO in solids.** → **Large ice-coated particles drift towards host star.** → **Enhanced abundance of CO gas is accreted onto the host star.** → **Particles lose volatile ice content once they drift past the midplane CO snow line.**

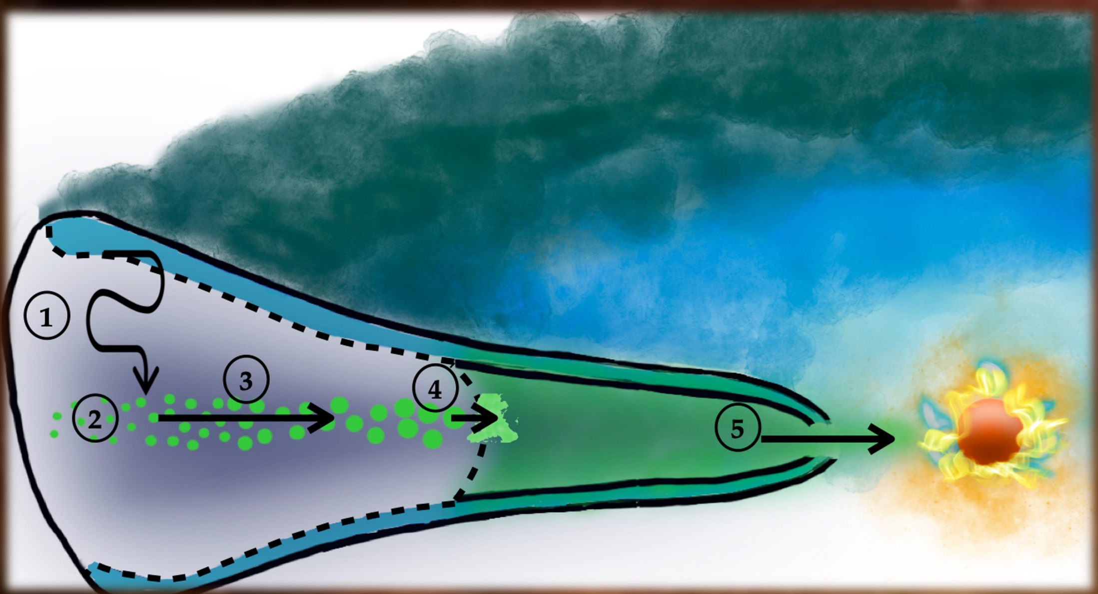

*Figure 1 – The **physical evolution** of CO in protoplanetary discs. Figure reproduced from Powell et al. (2022).*

Background

- ALMA observations reveal significant CO depletion in protoplanetary discs, up to 100x lower than in the ISM (e.g., Kama et al. (2016)).
- Figure 1 shows the physical evolution of CO, where freeze-out on large grains is a potential mechanism for depletion, requiring gaseous CO diffusion to the midplane. This is influenced by turbulence strength, with studies (Krijt et al. (2020); Van Clepper et al. (2022)) indicating that strong turbulence with $\alpha = 10^{-3}$ is needed to cause significant depletion on Myr timescales.
- ALMA continuum observations of mm-sized dust grains suggest weaker midplane turbulence with $\alpha < 10^{-3}$ (and possibly $\alpha < 10^{-4}$), as indicated by studies such as Pinte et al. (2016), Villenave et al. (2022), and Pizzati et al. (2023), among others.
- MHD winds are therefore thought to play a key role in the outer regions of discs, but their impact on disc composition is not fully understood.
- Figure 2 compares viscous and wind-driven discs: viscous discs rely on turbulence for angular momentum transport, while wind-driven discs depend on MHD winds.
- It is expected that in wind-driven discs, weak turbulence will reduce the effectiveness of CO diffusion to the midplane. However, winds can carry away CO as mass is lost from the disc surface. It is not known which of these two effects is dominant.

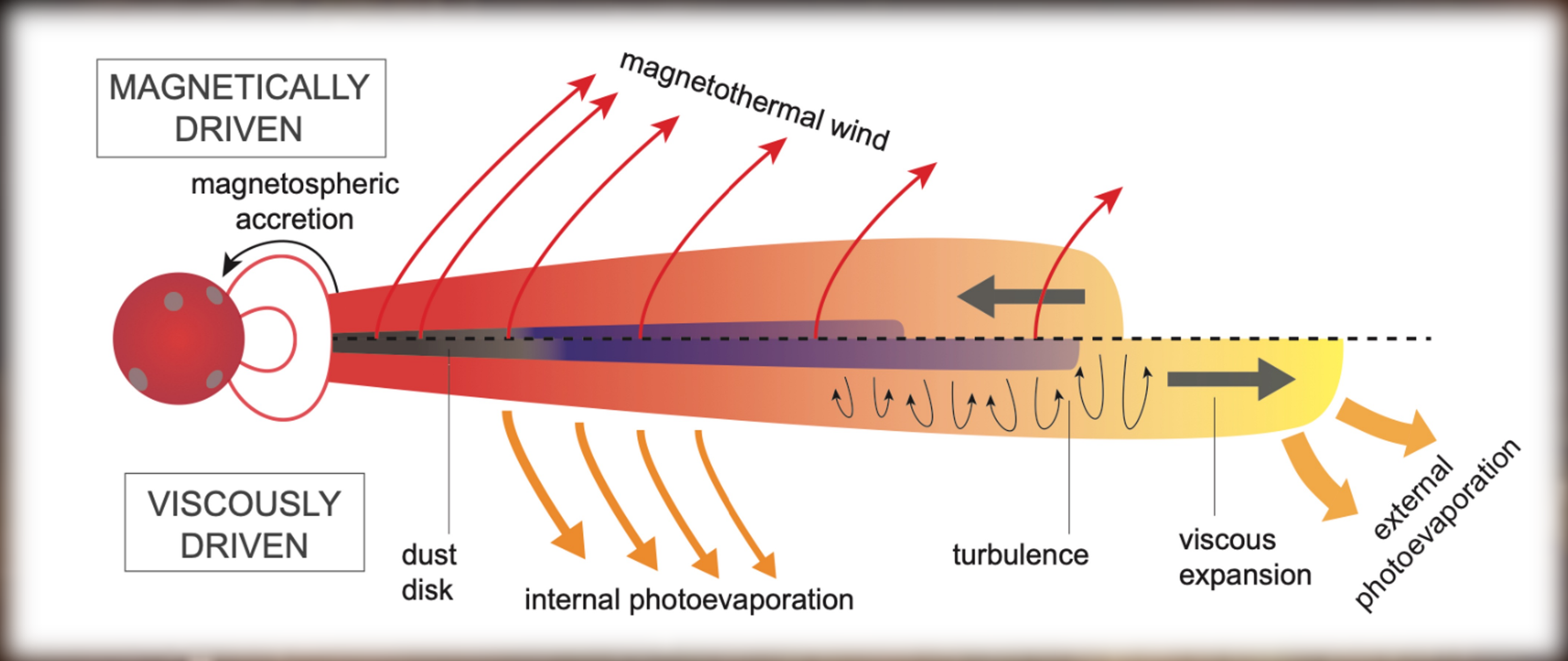

Figure 2 – Schematic of two distinct evolutionary models for protoplanetary discs. Taken from Manara et al. (2023).

Methodology

- To investigate CO depletion, a full dynamic model is in development, incorporating vertical settling, dust diffusion, grain growth, and ice adsorption and desorption processes using cuDisc (Robinson et al., 2024).
- cuDisc solves the hydrodynamic equations and dynamically updates the temperature structure over time.
- A wind is simulated by specifying a mass loss rate and allowing mass to exit the system without re-entry. A higher mass loss rate represents a stronger wind (Booth et al. 2021), and this is used to calculate the vertical velocity of the gas via mass conservation.
- Simulations of gas/dust dynamics in viscous and wind-driven discs have been run with $\alpha = 10^{-3}$ at 10 AU from a 1 $M_{\odot}$, 1 $L_{\odot}$ star, tracking the disc's evolution over 50,000 years until a steady state is achieved.
- A total of 100 grain sizes have been modelled in 100 vertical cells.

References

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What is the evolutionary difference between wind-driven versus viscous discs?

- Figure 3 - Top panel (viscous disc): dust size distribution changes over time, with larger grains settling at the midplane due to weaker gas coupling.
- Figure 3 - Bottom panel (wind-driven disc): similar trend, but with a higher density of smaller grains in the upper layers, as grains are entrained in the wind.
- Figure 4 - Grain size density comparison: small grains show a decrease similar to gas density in both discs. In the wind-driven disc, small grains are more concentrated at greater heights, while the wind has little effect on larger grains.
- Figure 5 - Temperature profiles: the midplane temperature is similar in both discs, as expected, since it is only gradually heated by reprocessed radiation. The wind-driven disc has cooler surface layers due to a different grain size distribution in the upper layers. The presence of larger grains helps the dust cool.
- Note: The initial conditions used here are too warm for freeze-out.

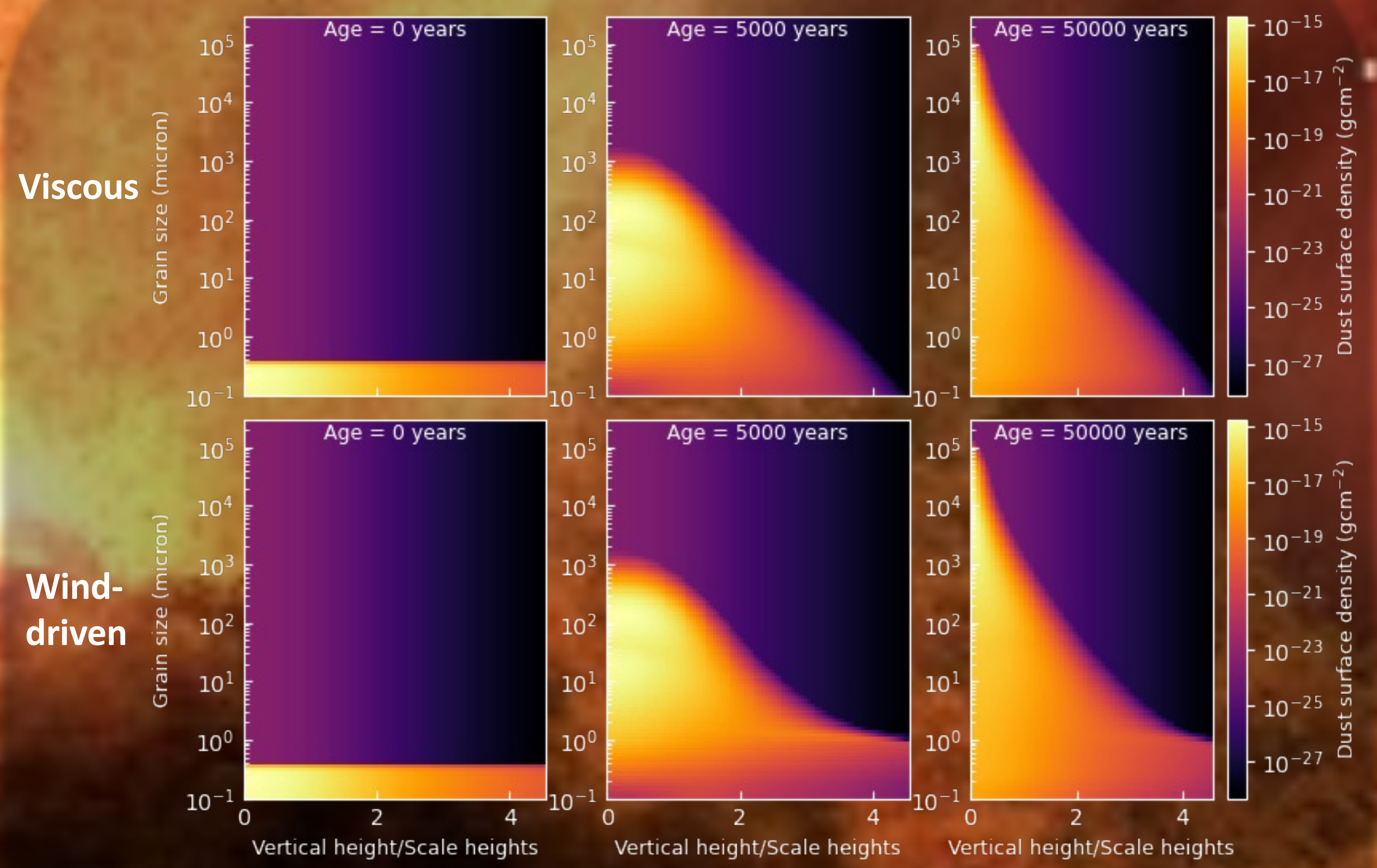

Figure 3 – Results showing the evolution of grain sizes at different time steps in the simulation.

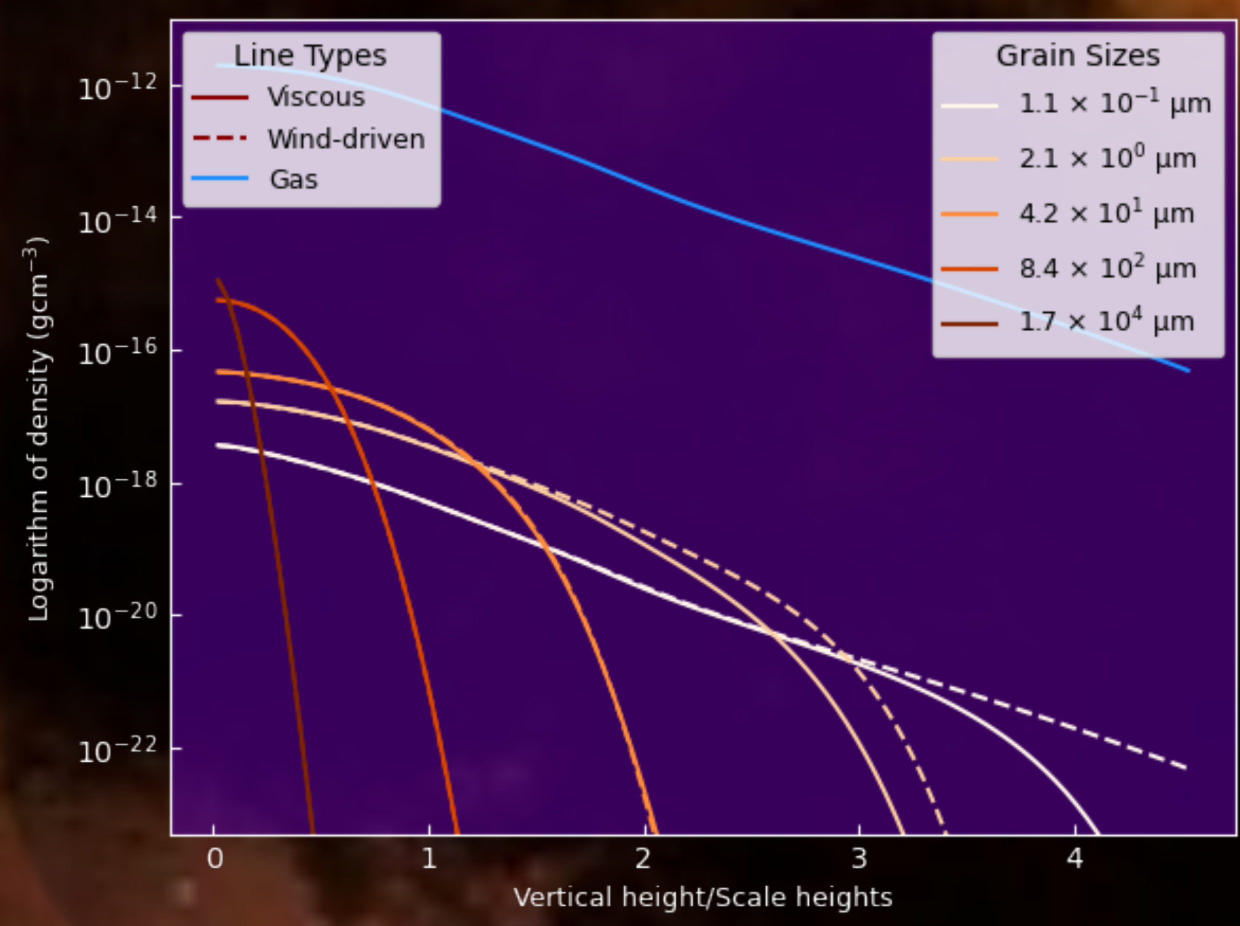

Figure 4 – Comparison of the density distribution of different grain sizes in the viscous and wind-driven models at steady state.

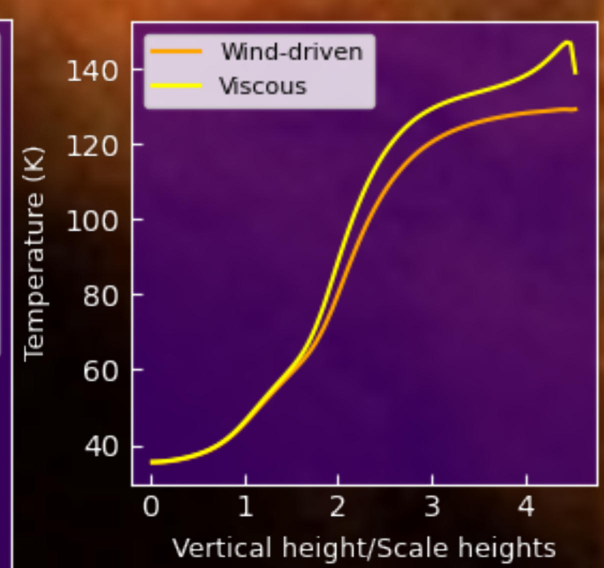

Figure 5 – A comparison of the vertical temperature profiles of the viscous and wind-driven discs at steady state.

Summary

- Successfully developed a functional cuDisc model for wind-driven discs.
- Comparison with viscous discs shows differences in grain behaviour and temperature. However, these differences in the upper layers may not significantly impact CO depletion, as CO remains in the gas phase in those regions.

Next Steps

- Use cuDisc to model CO freeze-out by calculating condensation and sublimation rates on dust grains.
- Postprocess the results with a full chemical code to analyse the chemical and physical evolution of CO.

Expected Outcome

- Faster CO depletion is anticipated in wind-driven discs compared to weakly turbulent discs without winds.

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Background image: *NASA/JPL-Caltech/R. Hurt (SSC/Caltech)*