Dust Entrainment in Externally Photo-Evaporated Proto-Planetary Discs

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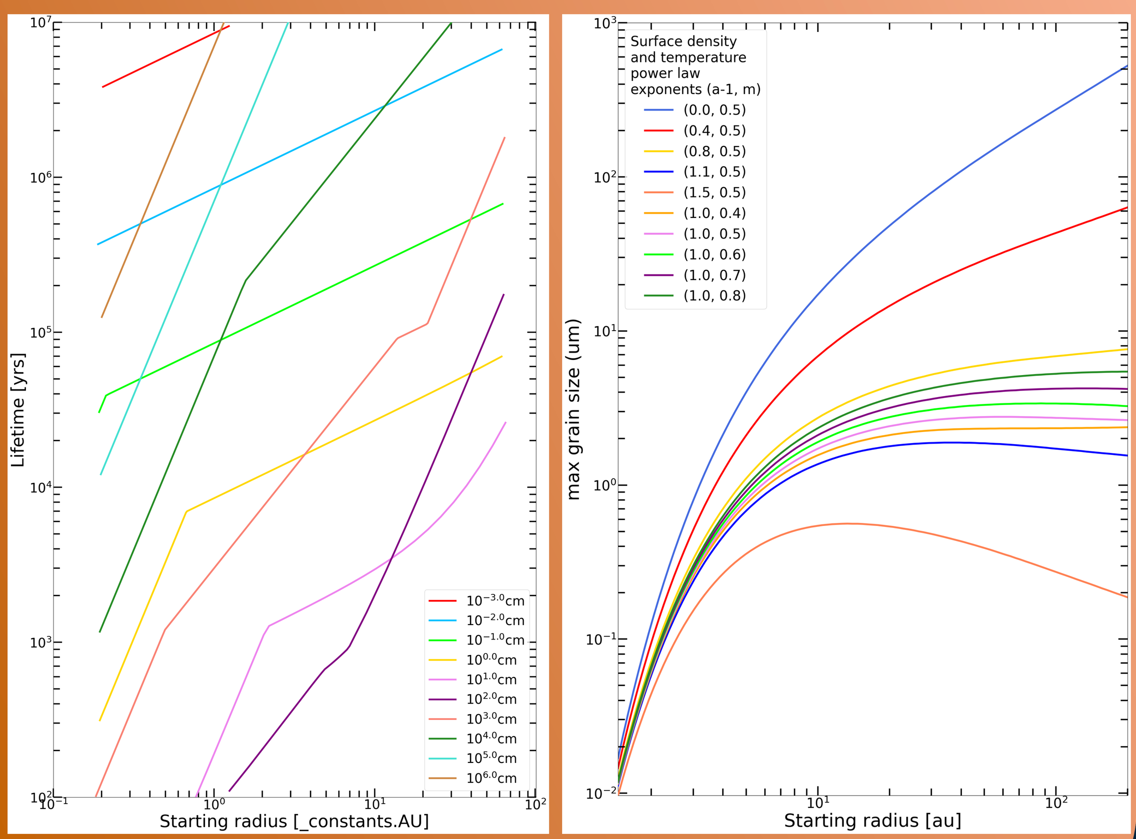
Abstract

- The environment in which proto-planetary discs evolve plays a crucial role in their evolution.
- Planets form in short-lived discs around young stars.
- One important mechanism for dispersing the disc is external photo-evaporation from nearby large stars.
- This heats the disc and entrains (carries out) dust, reducing the available mass for forming planets.
- The dust also shields the disc from further radiation, forming a feedback loop.
- In this work, we validate an existing analytic solution and propose a modification to it.

Benchmarking Code

- A new code was developed and tested that it reproduced gravitational dynamics and dust experiencing aerodynamic drag and a disc wind.
- Orbits were tested to be stable over 10Myrs, conserving energy and angular momentum, as well as not precessing.
- Aerodynamic drag forces were benchmarked against Weidenschilling 1977, reproducing the same dust lifetimes over a wide range of dust sizes, starting distances and drag regimes.
- Disc wind was benchmarked against Hutchison et al.'s 2016 photo-evaporative wind model.



[Paine et al., in prep] [Paine et al., in prep]

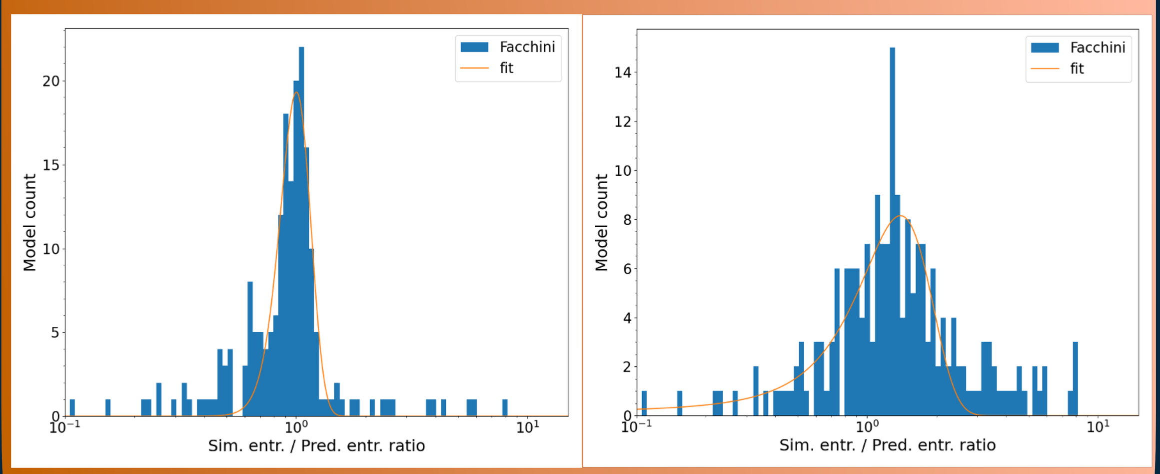
1D Model Results

- Dust is considered entrained when it reaches the escape velocity. Typically, entrained dust is on the order of a few microns.
- Facchini et al. 2016 derive an approximate formula for the maximum entrained dust size, given the properties of the disc and the wind:

$$s_{\max} \approx \frac{\bar{v}}{GM_*}\frac{\dot{M}}{4\pi\mathcal{F}\bar{\rho}}$$

- Crucially, the Facchini derivation discounts the centrifugal force to find a closed form solution.
- Haworth et al. 2023's FRIEDv2 1D models are semi-analytic, steady state hydrodynamical models of discs being externally photo-evaporated.
- Dust grains were placed at the disc edge, the base of the wind and the maximum entrained size was solved iteratively.
- **The models with dust started with no angular velocity were found to reproduce the Facchini solution.**
- **Importantly, the models started with Keplerian velocity were found to entrain dust about ~1.5 times as large as predicted by the analytic solution.**
- Interestingly, even larger dust sizes was found to stall in the wind, remaining in orbit at large radii. This will have implications on observations of evaporating discs and their predicted mass loss.

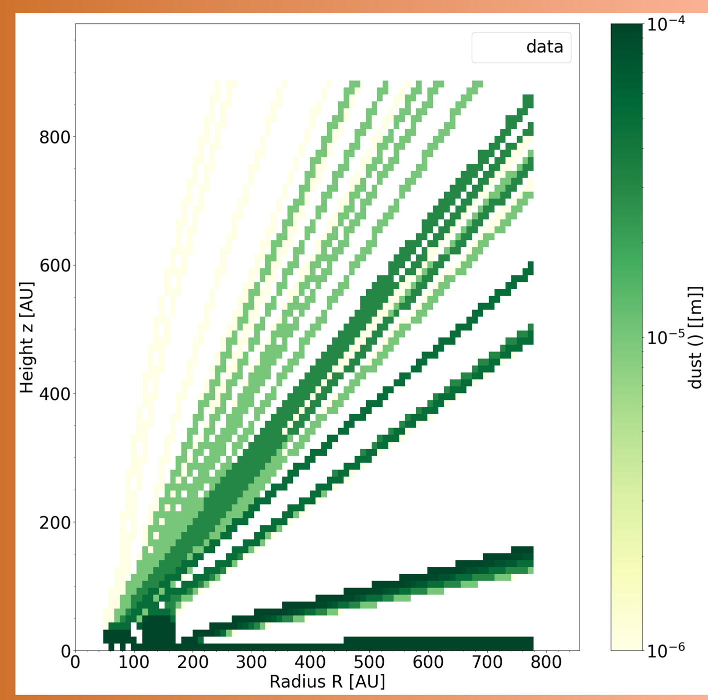
No angular velocity Models Keplerian velocity Models



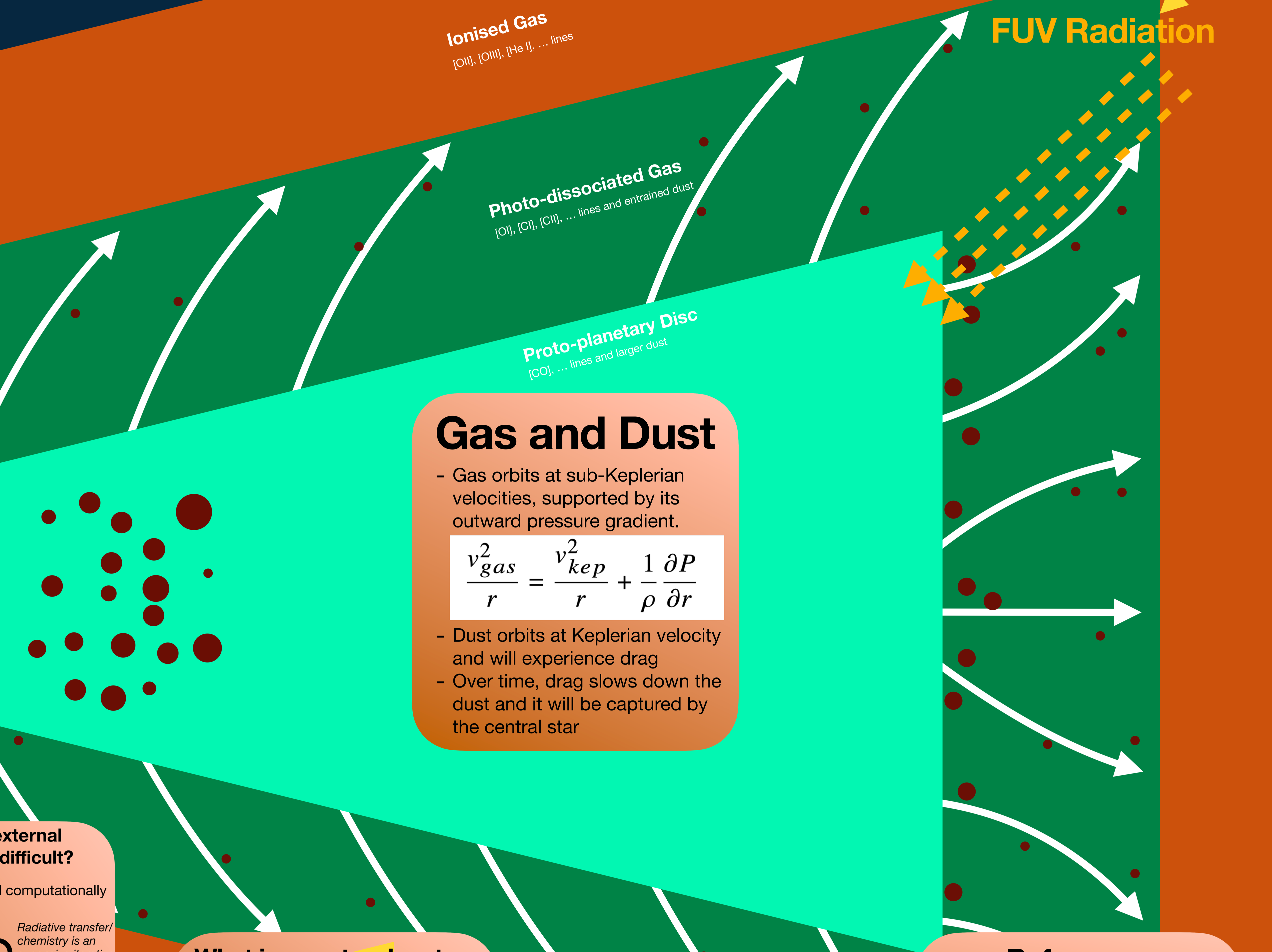
[Paine et al., in prep]

2D Model Results

- In 2D axisymmetric models, the vertical structure of the disc affects the dust entrainment.
- Preliminary models show the dust entrained from the disc surface to be roughly 10 times smaller than that entrained from the disc edge and midplane.
- Variations in dust entrainment throughout the disc could lead to observable structures and asymmetric shielding of the disc.



[Paine et al., in prep]



Gas and Dust

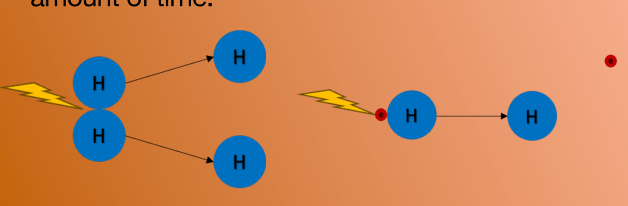
- Gas orbits at sub-Keplerian velocities, supported by its outward pressure gradient.

$$\frac{v_{gas}^2}{r} = \frac{v_{kep}^2}{r} + \frac{1}{\rho}\frac{\partial P}{\partial r}$$

- Dust orbits at Keplerian velocity and will experience drag
- Over time, drag slows down the dust and it will be captured by the central star

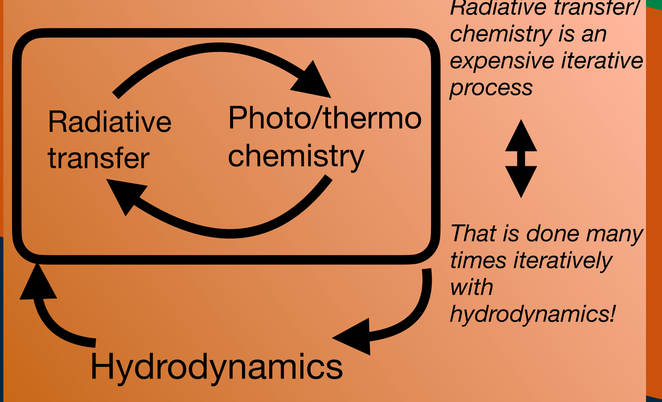
What is Photo-Evaporation?

- Far Ultraviolet (FUV) Radiation: 6-13.6eV, photo-dissociates Hydrogen (H_2 -> H + H).
- Extreme Ultraviolet (EUV) Radiation: 13.6eV-100eV, ionises Hydrogen (H -> H^+).
- X-Ray Radiation: 0.1-1keV, heats the disc and triggers chemical reactions.
- Gas is heated and expelled from the disc, dragging dust along with it.
- Internal photo-evaporation is due to the central star.
- External photo-evaporation is due to nearby stars, typically O and B-stars.
- Dust carried out to the edges of the disc will shield the interior of the disc from radiation, preventing further photo-evaporation.
- Creates feedback loop, where strong external photo-evaporation will protect a disc for a certain amount of time.



Why is modeling external photo-evaporation difficult?

It is technically challenging and computationally expensive!



It is computationally cheaper to add dust in pre-rendered models. This is justified since the dust feedback on the gas is expected to be negligible.

What is a proto-planetary disc?

- Stars form from collapsing gas clouds, leaving behind a disc of 99% H and He and 1% dust.
- The dust and gas becomes the mass reservoir from which planets are formed.
- Signatures of photo-evaporation are observed by looking at dust in the infrared and at specific chemical lines (e.g. CO, C[II], H_2)

What is dust?

- Small grains of silicates, metals and ices.
- Through collisions it can grow and fractionate.
- Can be sub-micron sized up to planet sized.

References

- Weidenschilling 1977, MNRAS, 180, 57W
- Facchini et al. 2016, MNRAS, 457, 3593
- Hutchison et al. 2016, MNRAS, 463, 2725H
- Winter & Haworth 2022, EPJP, 137, 1132W
- Haworth et al. 2023, MNRAS, 526, 4315H
- Paine et al. in prep (2024 hopefully…)