# Photophoresis boosts giant planet formation

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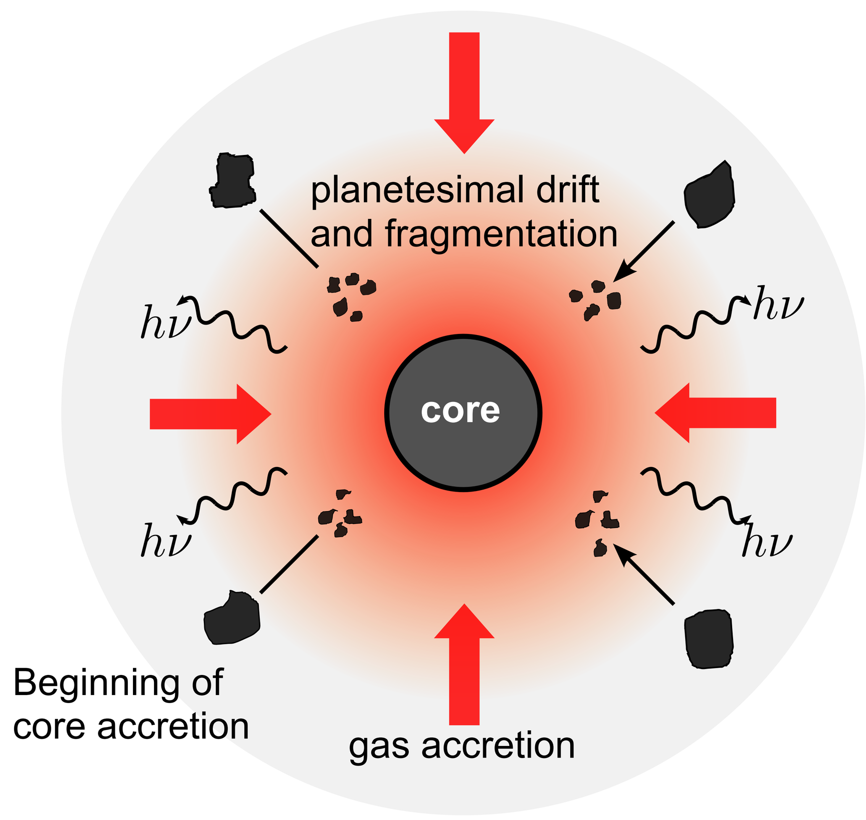
## Introduction

### 3 phases of giant planet formation

**1. Planetesimal accretion**
- builds up a solid core
- similar to formation of terrestrial planets

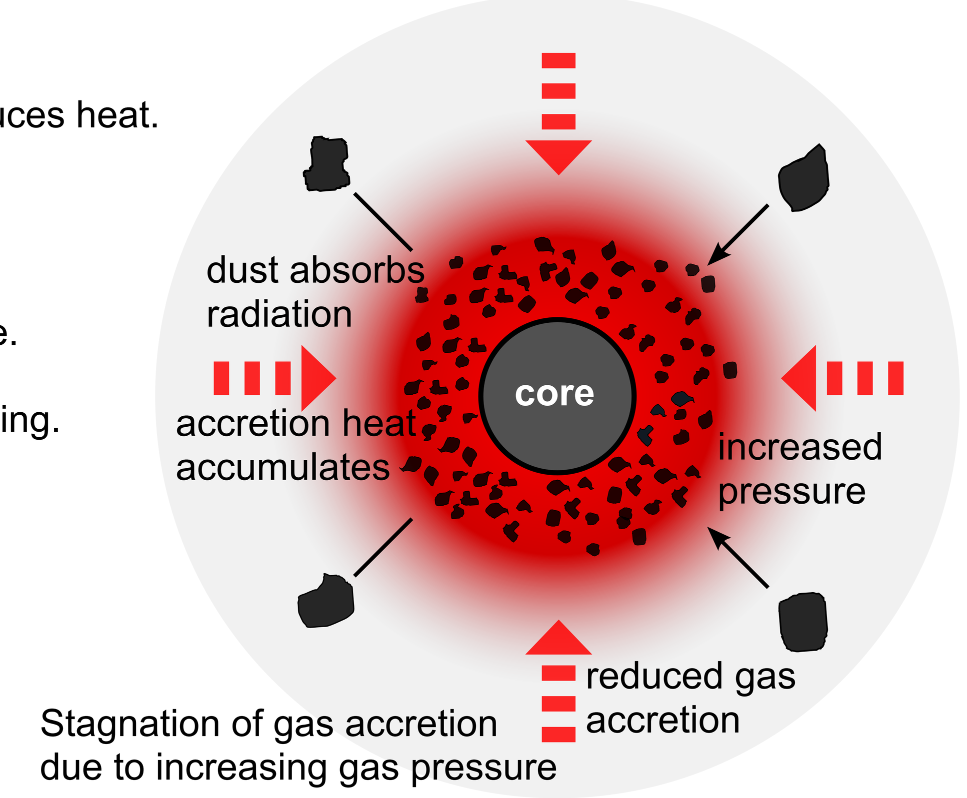
**2. Slow accretion of gas and planetesimals**
- core mass large enough to accrete gas
- atmosphere in hydrostatic equilibrium
- nearly constant accretion rate

**3. Runaway growth**
- from ice-giant (15 earth masses) to gas-giant
- approx. 1000 years [1, 2]




### Core accretion

- Accretion of planetesimals produces heat.
- Cooling works only via radiation.
- Fragmentation of planetesimals produces dust in the atmosphere.
- Increasing opacity prevents cooling.
- Increasing temperatures lead to growing gas pressure.
- Accretion rate is reduced by increasing gas pressure.
- timescales can be too large!!




## Basic equations

### Accretion model

- Model by Dodson-Robinson & Bodenheimer [3]
- Protoplanet at 15 AU radial distance to sun
- Accretion rate:

$$\dot{M}_{solid} = C_1 \pi \Sigma_{solid} R_c R_h \Omega$$

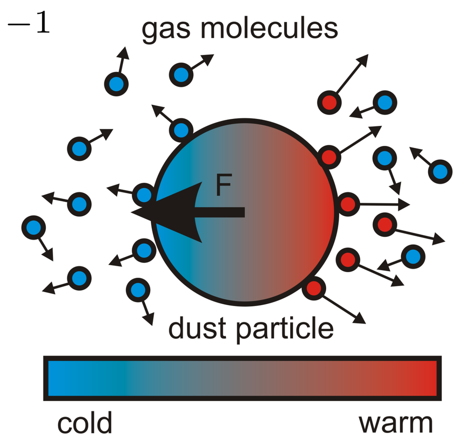
- Hill sphere: $R_h = a[M_{planet}/(3M_*)]^{1/3}$
- Capture radius: $R_c \approx 0.01 R_h$
- $C_1$ close to unity [4]
- Planetesimals deposit energy by gas drag heating, energy dissipation of ablated material and sinking of ablated material

### Photophoresis

$$F_{ph} = 2F_{max}\left(\frac{p_{max}}{p} + \frac{p}{p_{max}}\right)^{-1}$$

$$F_{max} = \frac{\pi \eta r^2 I}{2k_{th}} \cdot \sqrt{\frac{R_{gas}}{3TM_{mol}}}$$

$$p_{max} = \frac{\eta}{r}\sqrt{\frac{12R_{gas}T}{M_{mol}}} \quad [5]$$




- Interaction between particle and gas
- Momentum transfer between gas molecules and particle surface
- Net force from warm to cold
- Most efficient for $Kn$ = 1 ($Kn$ = free path / particle radius)

### Particle motion

- Photophoresis acts contra gravity: $F_{res} = F_{ph} - F_{grav}$
- constant drift velocity due to gas drag: $v_{drift} = a_{res} \cdot \tau$
- different gas coupling time ($\tau$) depending on Knudsen number:

$$Kn > 10: \quad \tau = 0.68 \cdot \frac{m_{dust}}{\pi r_{dust}^2 \rho_{gas} \nu_{gas}} = 0.91 \cdot \frac{r_{dust}\rho_{dust}}{\rho_{gas}\nu_{gas}}$$

$$Kn < 0.1: \quad \tau = \frac{m_{dust}}{6\pi r_{dust}\eta} = \frac{2r_{dust}^2\rho_{dust}}{9\eta}$$

$$0.1 \le Kn \le 10: \quad \tau = \frac{m_{dust}}{6\pi r_{dust}\eta} \cdot \left(1 + Kn \cdot \left(1.231 + 0.47e^{-1.178/Kn}\right)\right)$$

[6, 7, 8]

## Results

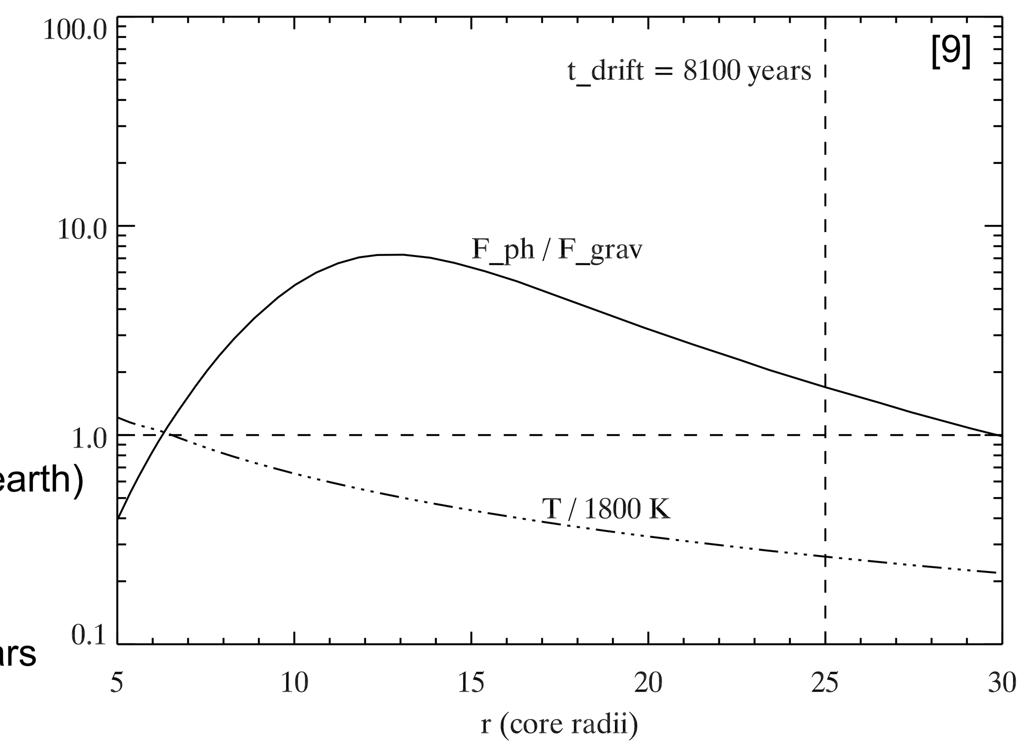
**Dust:**
- particle radius: $r$ = 10 μm
- density: $\rho$ = 2 g/cm3 (for porous olivine particles)
- thermal conductivity: $k_{th}$ = 0.1 W/Km (for porous aggregates)

**Gas:**
- Molar mass: $M$ =2.34 g/Mol
- Dynamic viscosity: $\eta$ = 1.8 x $10^{-5}$ Pa*s
- R = 8.31 J/mol K

**Radiation:**
Thermal radiation is calculated by the core accretion model

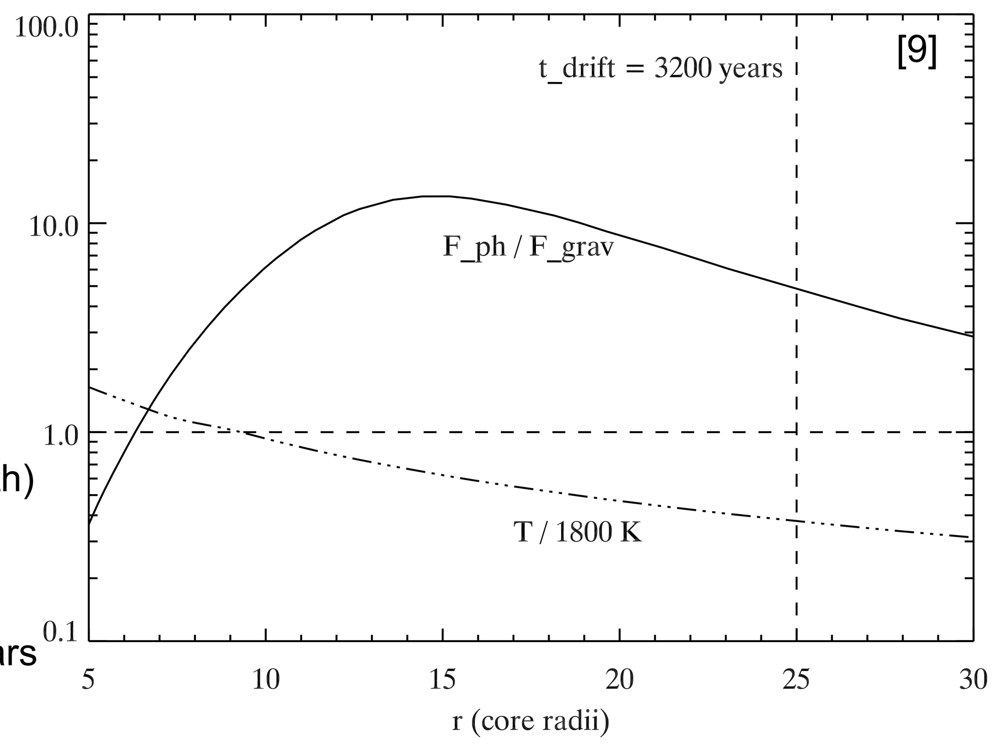
**Snapshot 1:**
- Radial distance: 15 AU
- formation time: 3.07 My
- m(core): 4.39 m(earth)
- r(core): 1.64 r(earth)
- m(atmosphere): 0.11 m(earth)
- r(equilibrium): 30 r(core)
- t(equilibrium): 3 * $10^4$ years

[9]



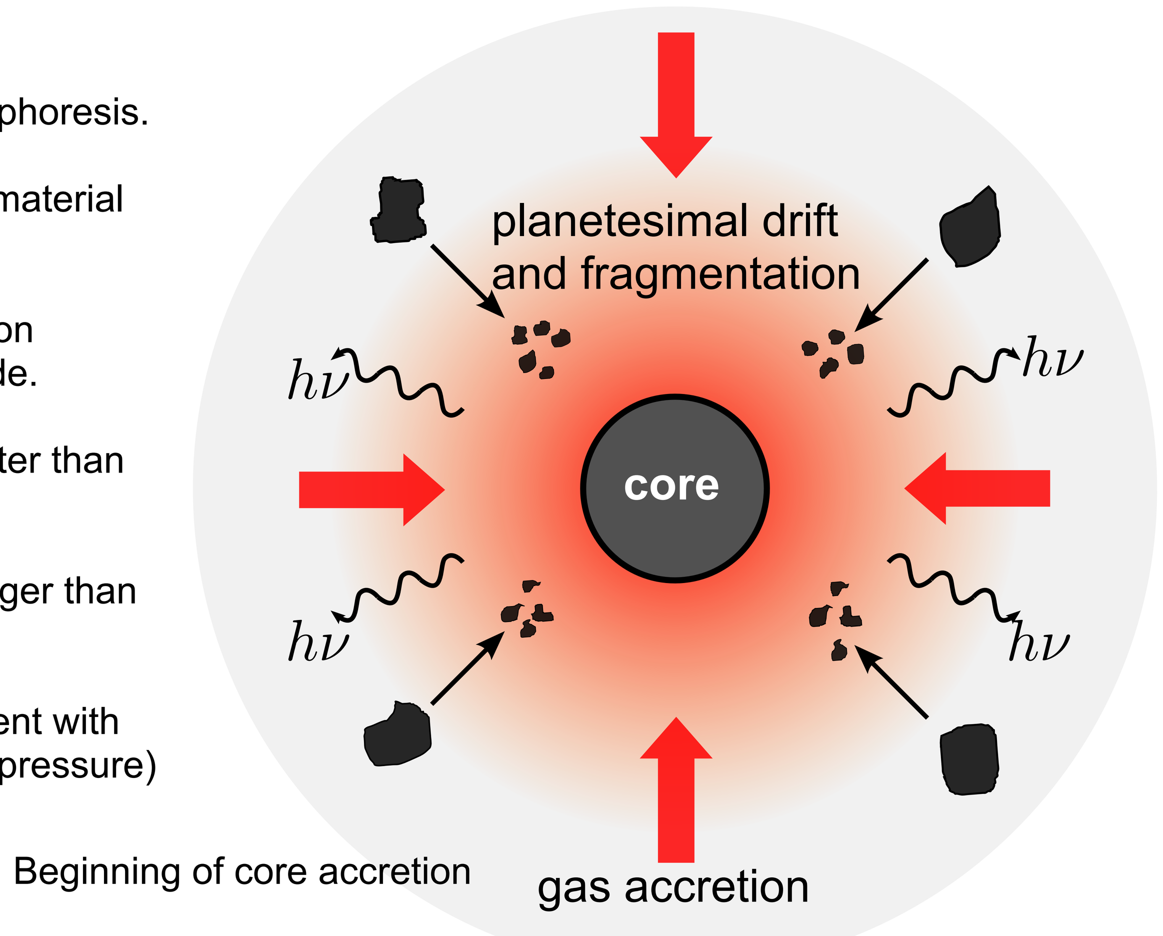

**Snapshot 2:**
- Radial distance: 15 AU
- formation time: 4.39 My
- m(core): 7.48 m(earth)
- r(core): 1.96 r(earth)
- m(atmosphere): 0.3 m(earth)
- r(equilibrium): 42 r(core)
- t(equilibrium): 3.3 * $10^4$ years

[9]

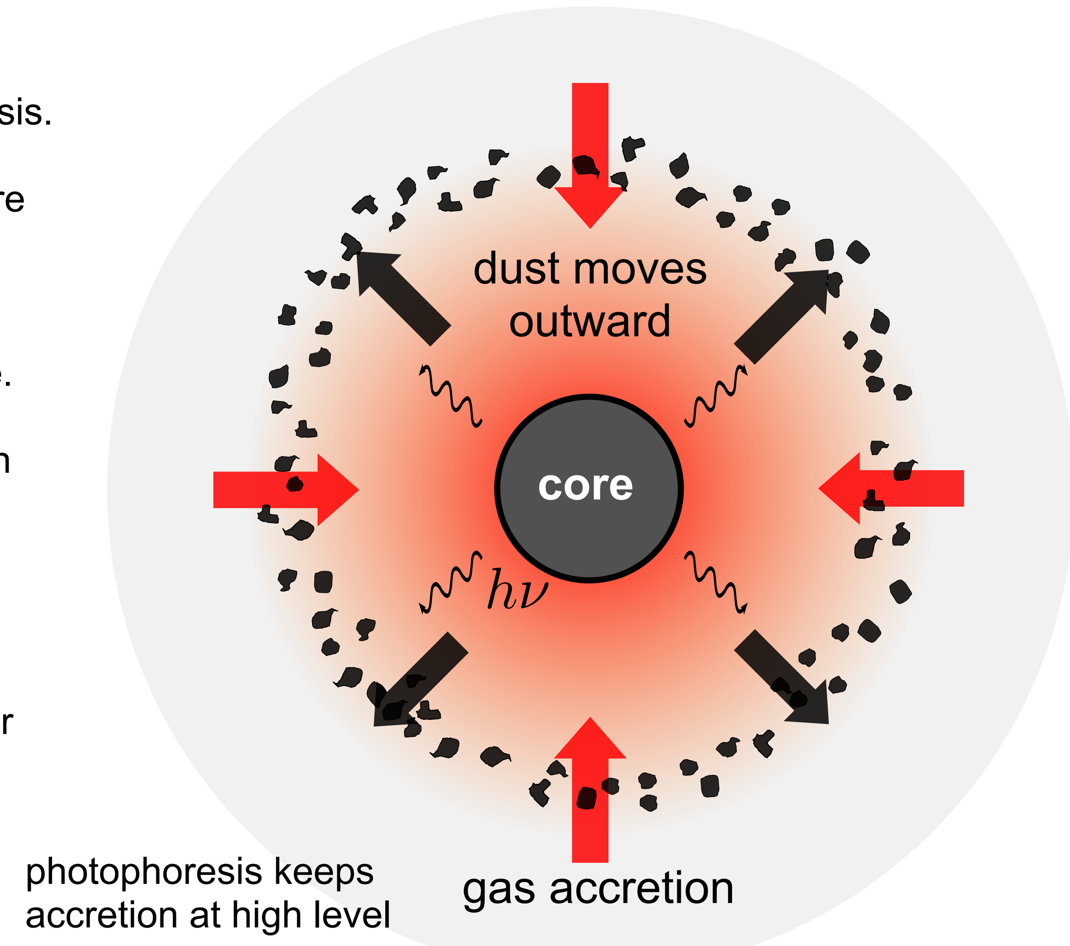



## Conclusions

- Thermal radiation drives photophoresis.
- Photophoresis is sufficient for material transport.
- Photophoresis exceeds radiation pressure by orders of magnitude.
- Drift timescales are much shorter than formation timescales.
- In the inner part pressure is larger than the optimum pressure $p_{max}$.
- photophoresis gets more efficient with growing distance (decreasing pressure)




- Dust is pushed outward by photophoresis.
- The opacity of the planetary atmosphere is strongly reduced.
- Thermal radiation is not absorbed within the inner part of the atmosphere.
- Inner atmosphere can cool via radiation
- No pressure increase.
- Gas accretion is not reduced.
- Further out photophoresis gets stronger due to pressure profile.
- Runaway process is possible.





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