From Disks to Planets
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How Shadowing and Illumination in Disks Affect Planet Formation

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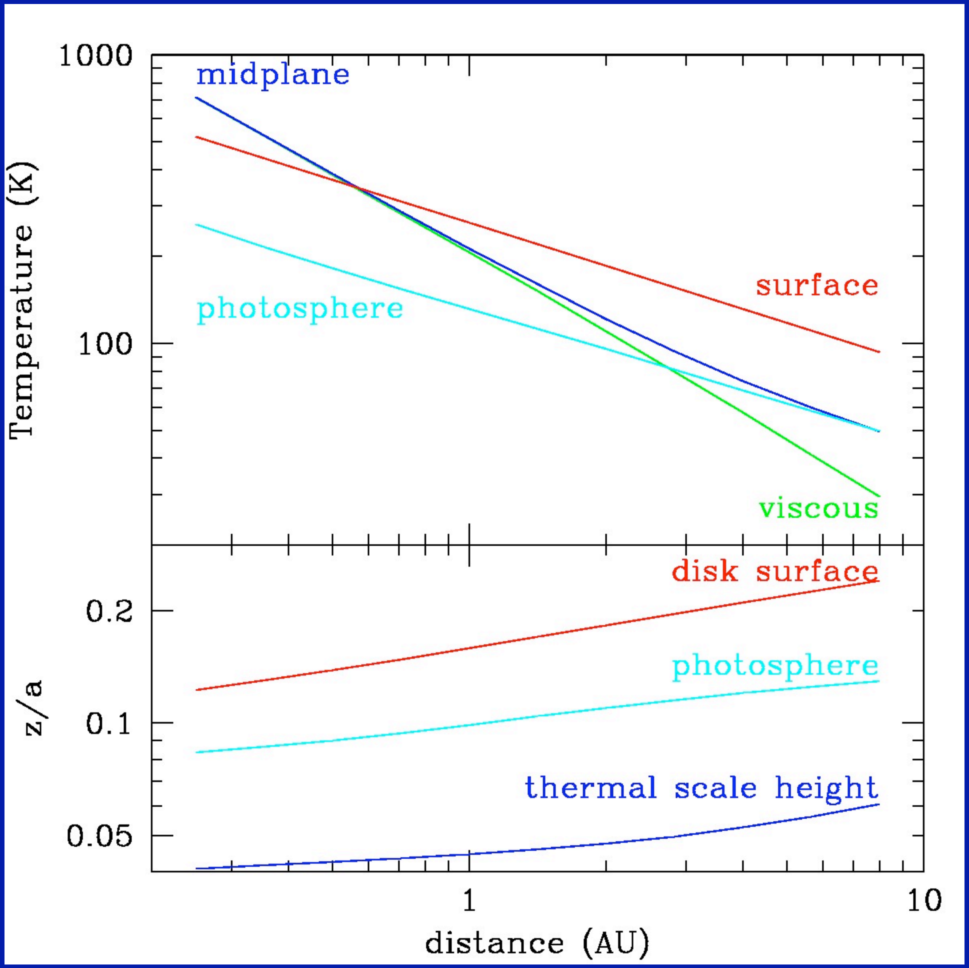
Overview

- Analytic models indicate that disks are **not vertically isothermal** (e.g. Calvet, D'Alessio; Chiang & Goldreich)
- Vertical temperature structure is primarily due to stellar irradiation
- **Protoplanets perturbing the disk can cause local temperature variations**
- **Temperature variations affect planet formation**

Temperature Structure

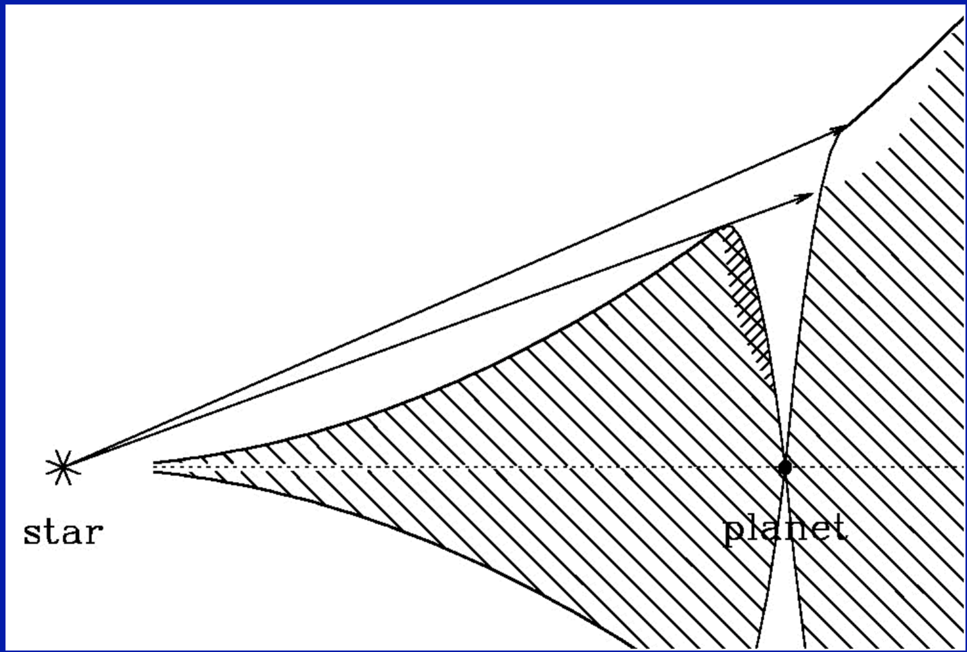


Jang-Condell & Sasselov 2004

- Viscous heating at the midplane
  - $\alpha_{SS} = 0.01$
  - $dM/dt=10^{-8}\ M_{sun}/yr$
- Stellar irradiation at surface
  - $0.5\ M_{sun}$
  - 4000K
  - $2\ R_{sun}$

Disk Perturbed by Planet

- Hydrostatic equilibrium
- Surface looks like a depression or well
- Shadowing (cooling) on near side, illumination (heating) on far side
- Consider planets below gap-opening threshold at 0.5 - 4 AU



Calculation of RT

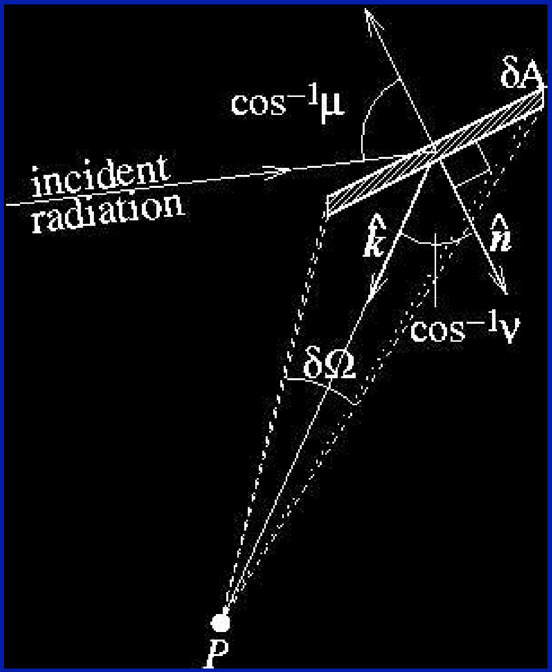
- Frequency separation
  - Short λ: κ_P, τ_s
  - Long λ: κ_R, τ_d
- For 1-D plane-parallel

$$\sigma T^4 = \pi B(\tau,\mu)$$

- Perturbed surface:

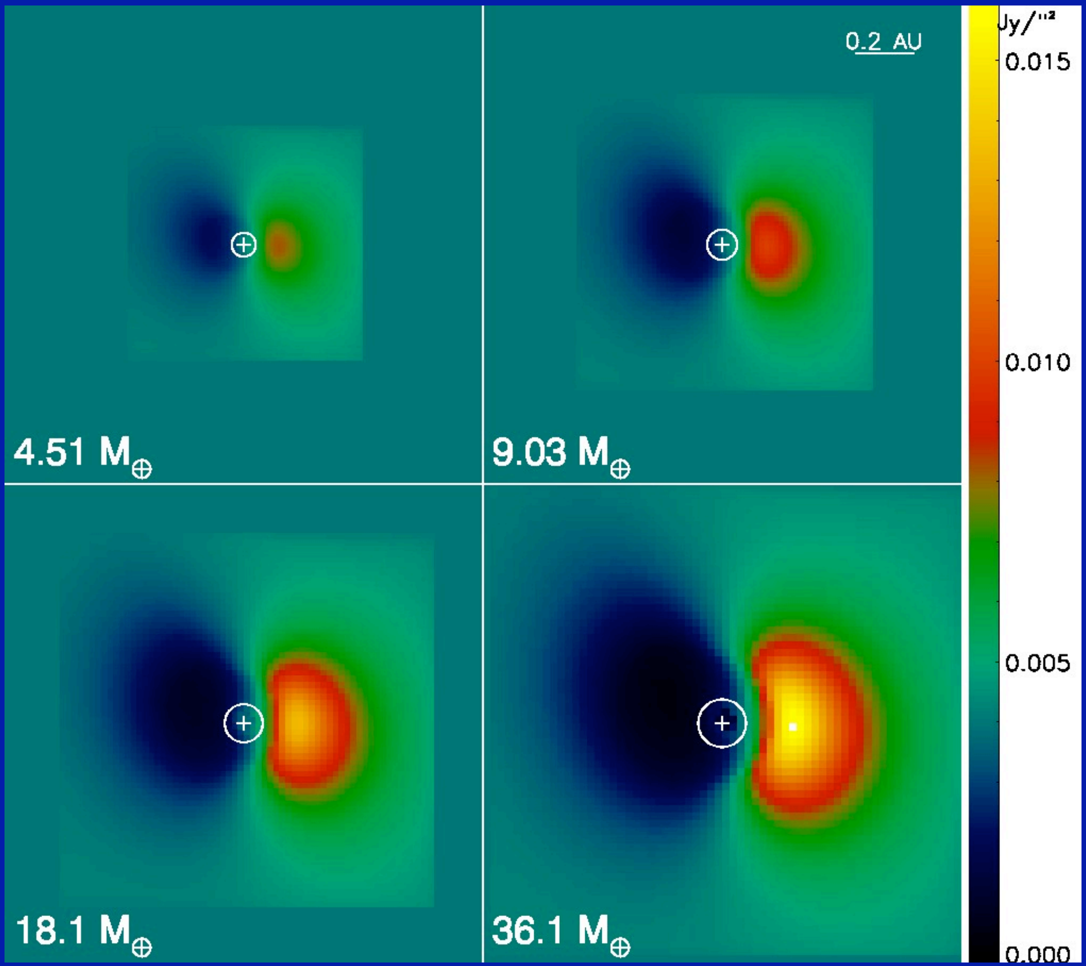
$$\sigma T^4 = \pi B_{tot} = \int B(\tau,\mu)\ \nu\ d\Omega$$

  - Sum over the surface



Synthetic Images: 4 AU, 30 microns

- At 100 pc,
  - need mas resolution
  - planet is 40 mas from the star
- Unlikely to be observable
- A gap may be resolvable (large planet)



Observability

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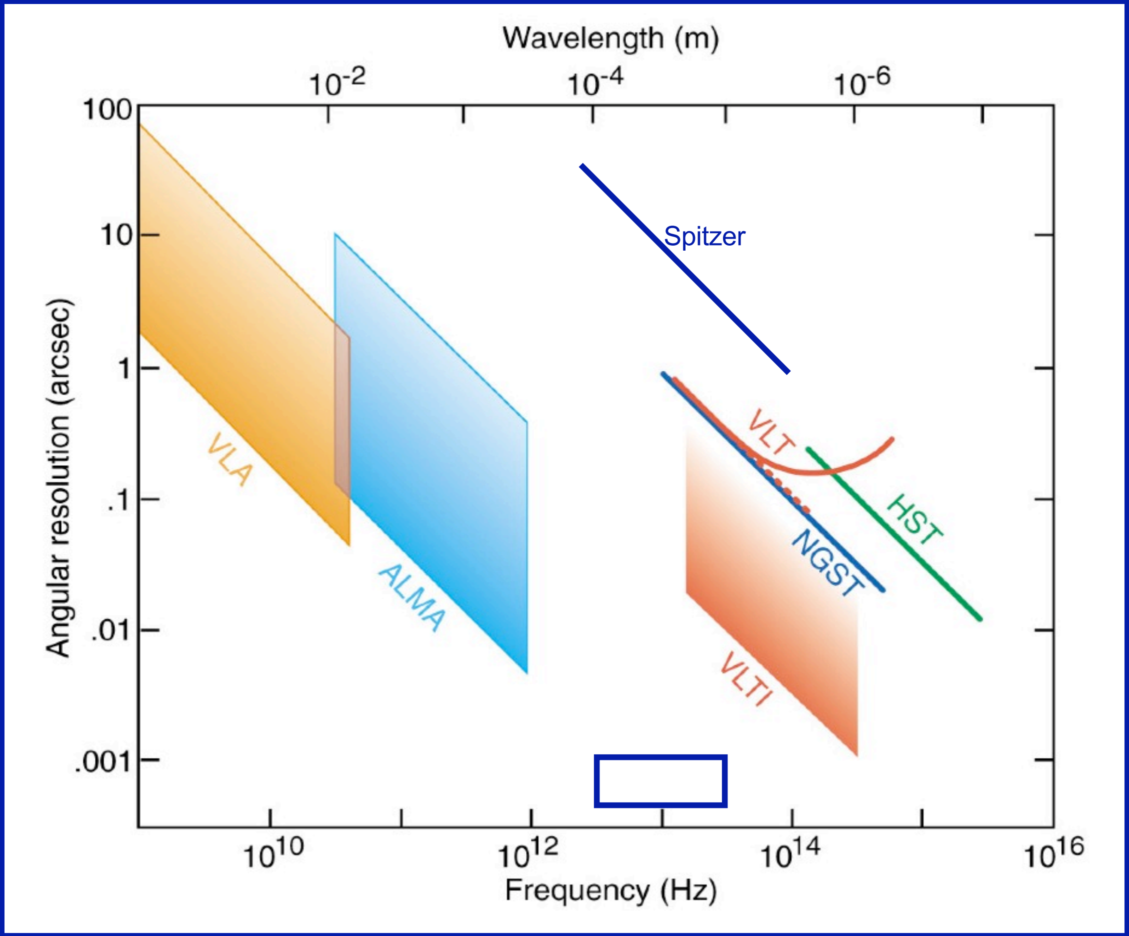


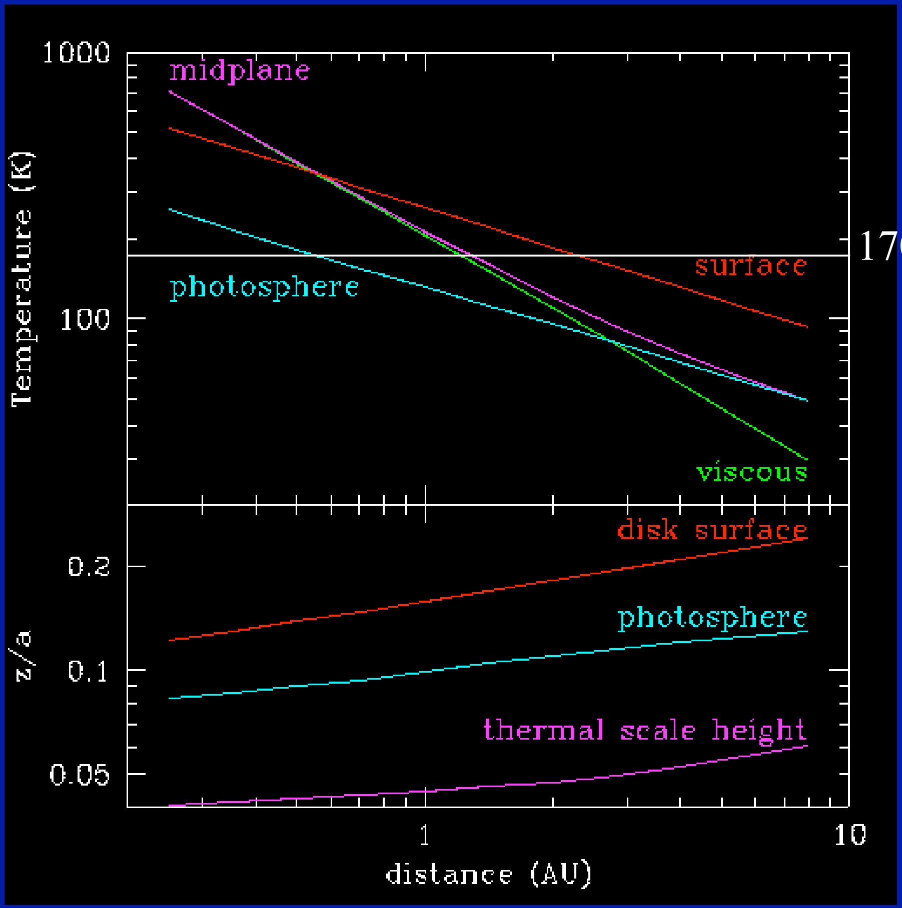
http://www.eso.org/projects/alma/science

Effects on Planet Formation

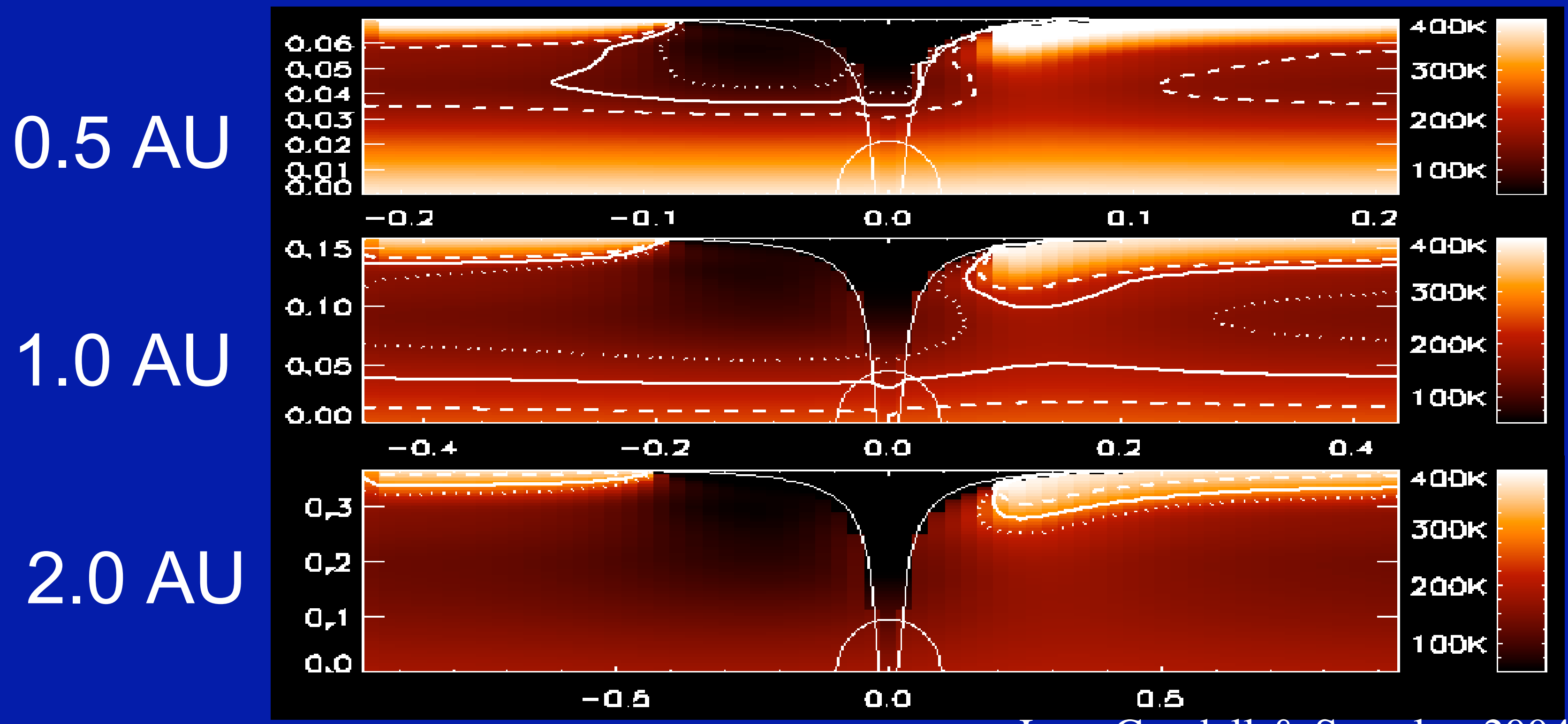
- May not be observable, but can affect:
  - Ice Formation
  - Planetary Migration

Ice Formation

- The snow "line" (170 K) in a 1-D disk occurs at 2.7 AU (Hayashi 1981)
- Model disk:
  - Snow transition begins at 0.6 AU
  - Midplane 1.3 AU
  - Surface 3.3 AU



Hot and Cold Spots



Jang-Condell & Sasselov 2004

Ice sublimates at 170 K (solid contour)

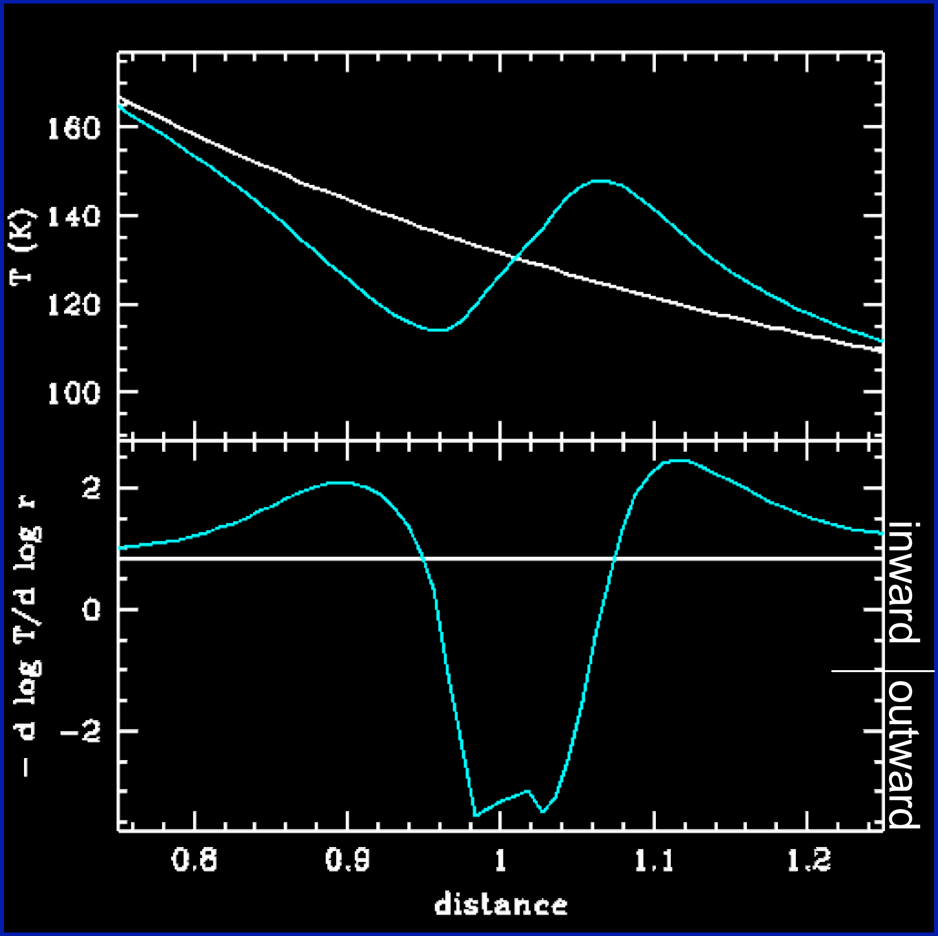
Define a hot (cold) spot as a region that is above (below) 170K where it would normally be below (above) 170K

Implications for Planet Growth

- Moving the snow line
  - Ice may be able to condense closer to the star than previously expected
- Cold and Hot spots
  - Condensation/sublimation of ice
  - Enhancement/decrement in abundance of solids
  - Increase/decrease in accretion rate
  - Increase/decrease in volatile fraction

Type I Migration

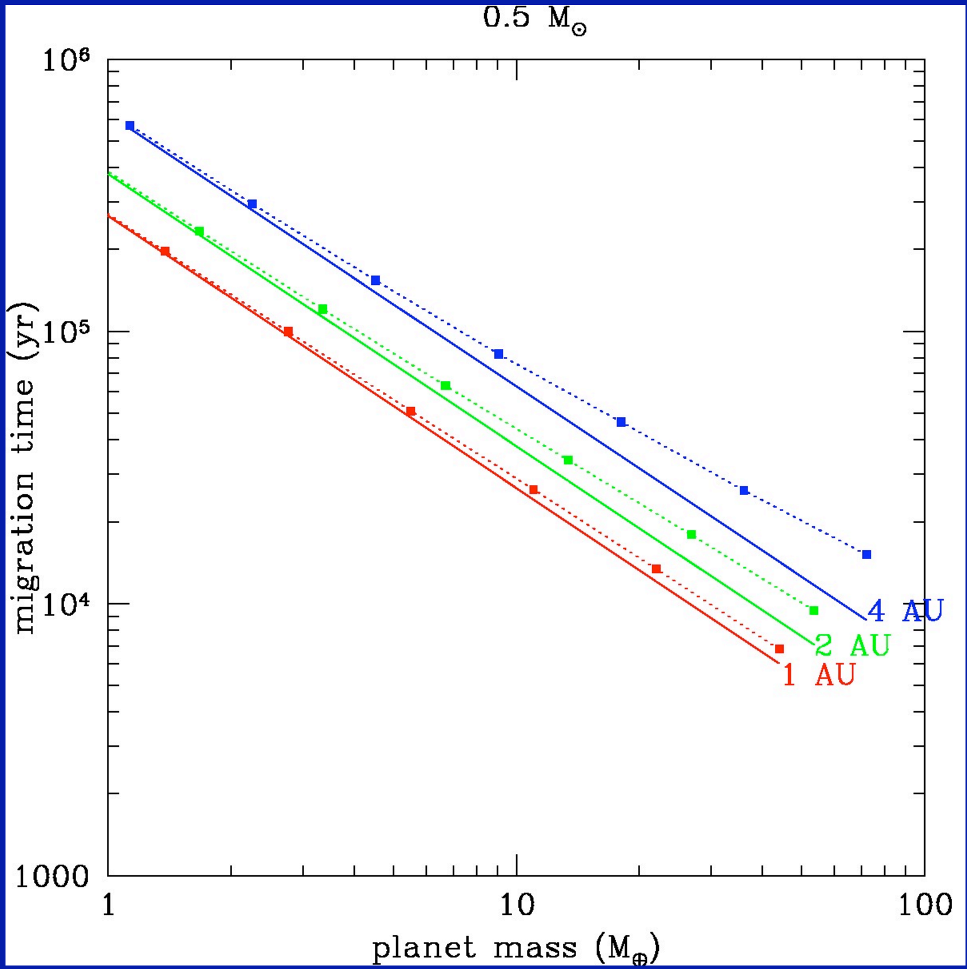
- Balance of tidal torques depends on pressure gradient in the disk
- A local inversion of the temperature gradient due to shadowing and illumination effects may slow or reverse inward migration



Migration Rates

Jang-Condell & Sasselov 2005

- Type I migration rates are sensitive to changes in the pressure gradient
- Local temperature inversion slows migration
- Up to a factor of 2 increase in migration timescale



Summary

- Temperatures near a protoplanet are sensitive to shadowing/illumination. This affects:
- Growth of protoplanets
  - Composition of disk material accreted
  - Rate of growth
- Planet migration rates
  - Can slow Type I migration

Future Prospects

- Varying parameters:
  - 1 M_{sun} -- Planet formation in Solar System
- Observable signatures of shadowing/illumination
  - Distinguishing planets, clumps
- Modelling disks with inner holes or gaps
  - Hot inner walls, self-shadowing
- Numerical simulations
  - Non-linear effects
  - Feedback, self-consistency

Neglected Physics

- Dynamical interactions
- Accretion onto the planet
- Non-linear effects (i.e. density waves, gap-opening)
- Self-consistency -- response of density to temperature
- RT between hot/cold spots