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

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

Jang-Condell & Sasselov 2004
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 $\lambda$: $\kappa_P$, $\tau_s$
  - Long $\lambda$: $\kappa_R$, $\tau_d$

- For 1-D plane-parallel
  $$\sigma T^4 = \pi B(\tau, \mu)$$

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

• 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:
  – $1 \, M_{\text{sun}}$ -- 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