Monte Carlo Radiation Transfer in Protoplanetary Disks: Disk-Planet Interactions, Structure and Warping

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Radiation Transfer + Hydrodynamics

RT Models: Barbara Whitney, Jon Bjorkman, Christina Walker, Mark O’Sullivan

Dust Theory: Mike Wolff

SPH Models: Ken Rice, Mike Truss, Ian Bonnell

Observations: Charlie Lada, Ed Churchwell, Glenn Schneider, Angela Cotera, Keivan Stassun
Monte Carlo Development History

• Scattered light disks & envelopes (1992)
• 3D geometry & illumination (1996)

• Dust radiative equilibrium (2001)
• Monte Carlo for disk surface + diffusion for interior (2002)

• Density grids from SPH simulations (2002)
• Spatial variation of dust opacity (2003)
• Self consistent vertical hydrostatic equilibrium (2003)
Disk Structure Calculations

• Above used parameterized disks: power laws for $\Sigma(r), h(r)$
• Disk theory: reduce model parameter space
• Irradiated accretion disks: $\Sigma \sim r^{-1}, h \sim r^{1.25}$ (D’Alessio, Calvet, & collaborators)
• New Monte Carlo: iterate for disk structure (Walker et al. 2004)
• Model disks around GM Aur and AA Tau
Disk-Planet Interactions: Gap Clearing

Simulation from Ken Rice & Phil Armitage

Papaloizou, Lin, Bodenheimer, Lubow, Artymowicz, Nelson, D’Angelo, Kley, ...

• Observational signatures: images, SEDs?
Protoplanetary Disks

- Need high resolution imaging: ALMA
- Gap clearing simulation images:

700 µm

700 µm ALMA simulation

Wolf et al. 2002
Inner Gaps from SED Modeling

• Remove inner disk material: remove near-IR excess emission

\[ R_{\text{in}} = 7R_* \]
\[ R_{\text{in}} = 4 \text{ AU} \]

GM Aur
GM Aur: Disk/Planet Interaction?

- NICMOS coronagraph
- Scattered light modeling:
  - $M_{\text{disk}} \sim 0.04 M_8$; $R_{\text{disk}} \sim 300$ AU; $i \sim 50$

Schneider et al. 2003
GM Aur: Disk/Planet Interaction?

- No near-IR excess
- SED model requires 4AU gap: planet?
GM Aur: Disk/Planet Interaction?

- 3D SPH calculation from Ken Rice
- Planet at 2.5AU clears inner 4AU in ~2000 yr

Rice et al. 2003
GM Aur: Disk/Planet Interaction?

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Rice et al. 2003
GM Aur: Disk/Planet Interaction?

- Spitzer SED can discriminate planet mass
- Centroid shifting $\sim 0.1$mas: Keck, SIM?

$M_p = 2M_J$  $M_p = 50M_J$

Rice et al. 2003
GM Aur: Disk/Planet Interaction?

- *Spitzer* SED can discriminate planet mass
- Centroid shifting $\sim 0.1\text{mas}$: Keck, SIM?

Rice et al. 2003
Calvet et al. 2002
AA Tau: Large and Small Scale Disk Structure

- Photopolarimetry (Bouvier, Menard, et al.)
  \[ P \sim 8.4 \text{ days}, \Delta V \sim 1 \text{ mag}, \Delta(B-V) \sim 0 \]
  Star eclipsed by warp in inner disk
- SED model to get disk structure
- Warped disk model for photopolarimetry
- SPH: tilted dipole warps disk
AA Tau SED Modeling

- $T = 4000 \, K$, $R = 2R_8$, $M = 0.5M_8$
- $M = 2e-9 \, M_8/\text{yr}$, $R_d = 200 \, \text{AU}$, $i = 70$

O’Sullivan et al. (2004)
Analytic Disk Warp

• AA Tau: $P \sim 8.4$ days
• Warp at $r \sim 0.07$ AU, amplitude $\sim 0.02$ AU
Photopolarimetry Simulation

$\Delta V \sim 1 \text{ mag}$
$\Delta P \sim 0.3\%$

O’Sullivan et al. (2004)
SPH Simulation

• Inclined dipole field: include magnetic force in SPH code (NOT MHD!)
• Need $B = 2 \text{ kG}$, at latitude $\theta = 65$ (see also Terquem & Papaloizou)
Summary & Future Research

• Monte Carlo: self-consistent disk structure calculations
• GM Aur: Disk-planet interaction, need Spitzer SEDs
• AA Tau: SED model for disk structure
  Warped disk for photopolarimetry
  SPH: dipole $B = 2$ kG, at latitude $\theta = 65$
• Coding: Radiation pressure
  Include gas opacity
  Transiently heated grains
• Goal: merge radiation transfer & hydro
• Codes now available at:
  http://gemelli.spacescience.org/~bwhitney/codes
Disk Dust: Grain Growth

--- --- --- --- ISM

--- --- --- --- Disk dust

Dust Size Distribution:
Power law + exponential decay
Grain Sizes in excess of 50µm
Grayer opacity, Sub-mm slope $\sim 1/\lambda$

$$n(a) \sim a^{-p} \exp\left( -\left[ a/a_c \right]^q \right)$$
$$p = 3.5 \quad q = 0.6 \quad a_c = 50\mu m$$

Fits HH30, GM Aur, AA Tau

Beckwith & Sargent (1991): sub-mm continuum SEDs: $\kappa \sim 1/\lambda$
Estimating $R_{\text{in}}$ from SEDs

• Hot inner edge emits in IR
• Include inner edge emission when estimating $R_{\text{in}}$
Vertical Hydrostatic Equilibrium

Monte Carlo, $R_{in} = 4$ AU, $i = 0 - 50$

CG97, $R_{in} = 0.1$ AU

CG97, $R_{in} = 4$ AU
Estimating $R_{\text{in}}$ from SEDs

- MC models include inner edge emission
- Other models without inner edge emission
- No 10µm excess

- MC: $R_{\text{in}} > 10$ AU
- CG: $R_{\text{in}} \sim 2.5$ AU
Disk Structure

Walker et al. (2004)
Walker et al. (2004)
Comparison Summary

• MC: Disk slightly hotter at large radii
  Slightly more emission in 20-200µm

• Differences: Radiation pressure
  Dust opacity
  Treatment of upper layers
  Non-isotropic scattering
  Radial transport in outer disk