Monte Carlo Radiation Transfer in Protoplanetary Disks

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Radiation Transfer + Hydrodynamics

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

Dust Theory: Mike Wolff

SPH Models: Ken Rice, Mike Truss, Ian Bonnell

Observations: Rachel Akeson, 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) SEDs disks + envelopes
- Monte Carlo for disk surface + diffusion for interior (2002)
- Density grids from SPH simulations (2003)
- Spatial variation of dust opacity (2003)
- Self consistent vertical hydrostatic equilibrium (2004)
Disk Structure Calculations

• Our models used parameterized disks:
  \[ \Sigma(r) \sim r^{-p}, \ h(r) \sim r^\beta \]

• Disk theory: reduce model parameter space

• Irradiated accretion disks in vertical hydrostatic equilibrium (HSEQ): (D’Alessio, Calvet, et al.)
  \[ \Sigma \sim r^{-1}, \ h \sim r^{1.25} \]

• New Monte Carlo: iterate for self consistent disk structure (Walker et al. 2004, 2005)

• *How well can power law disks reproduce structure, SEDs and images of HSEQ disks?*
HSEQ vs Power Law Disks

\[ \Sigma(r) \sim r^{-1} \quad \Sigma(r) \sim r^{-4} \]

\(T = 10^4 \text{ K} \)

\(M_{\text{disk}} = 0.01 \, M_\odot\)
Temperature Structures

\[ \Sigma(r) \sim r^{-1} \]

HSEQ

\[ \Sigma(r) \sim r^{-4} \]

HSEQ

\[ h(r) \sim r^{1.25} \]

\[ h(r) \sim r^{1.2} \]
Inner Edge of Disk

- Inner edge is important for setting near IR excess (Natta, Dullemond, Dominik, & collaborators)
- Recent HSEQ models suggest a new class of disk where inner edge shadow dominates structure and SED (e.g., Dullemond & Dominik 2004)
Inner Edge of Disk

- Can reproduce HSEQ disk temperature structure, SEDs, and images with power law disks with monotonically increasing scaleheight $h = h_0 \left(\frac{r}{R_0}\right)^\beta$
- General recipe: scale $h(r)$ from hydrostatic value at dust destruction radius, $\beta = 1.2$ to $1.3$
- **HSEQ disks**: dust settling and disk surface density dominate over inner edge effects
- **Inner edge can shadow if outer disk not in HSEQ**
Group I & II Herbig Ae Disks

- Similar mm fluxes
- Group II: lower mid to far-IR fluxes
- **Mid to far IR SED: dust settling, disk viscosity?**

SED data compiled by Mike Sitko
T Tauri Disks: SED + Interferometry

- RY Tau: \( M_d = 0.015M_\odot \), \( M_{\text{acc}} = 2.5 \times 10^{-7} M_\odot /\text{yr} \)
- Inner disk: \( R_{\text{dust}} = 0.27 \text{ AU} \), \( R_{\text{gas}} = 5 R_* \)
- Gas opacity, inner edge, disk locking models
- *Gas emission inside dust fits PTI 2.2\( \mu \text{m} \) data*

Akeson et al. (2005)
3D Models: Fractal Clouds

- Big variations with viewing angle in optical to IR SED and silicate features

Whitney et al. (2005)
Disk Candidates from GLIMPSE?

- 314.20+0.34
- 305.96+0.27

IRAC 1,3,4

2MASS JHK
Disk Candidates from GLIMPSE?

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• Are these images of:
  – Very large, distant disks: $R_d \sim 10^4$ AU?
  – Smaller, nearby disks: $R_d \sim 1000$ AU?
  – Junk?

IRAC

$R_d = 1000$ AU
$d = 58$ pc

$R_d = 15000$ AU
$d = 1$ kpc
Summary

• Monte Carlo: self-consistent disk structure calculations
• Dust settling and $\Sigma(r)$ dominate mid & far-IR SED
• Interferometry: emission from inner gas disks
• Huge disks from GLIMPSE?

Codes now available at:
http://gemelli.spacescience.org/~bwhitney/codes