Spectral Synthesis for Protoplanetary disk models

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Incoming radiation

- X-Rays
- Absorption by gas
- Scattering
- Scattering by dust
- Absorption by gas and dust
Incoming radiation

Cosmic Rays

Interstellar UV
Outgoing (reprocessed) radiation
e.g. Kamp et al 2013
Bergin et al 2007

CO low J sub mm

CO ro-vib 2-5μm
CO high J

H$_2$O

H$_2$O from neutral-neutral reactions

[OI] 63μm

H$_2$O from photodesorption

[CII] 157μm

e.g. Kamp et al 2013
Bergin et al 2007
Summary

3D hydrodynamical Models

Hydrostatic modeling (Radiative transfer, chemistry)

Spectral synthesis - SEDs, detailed spectra
3D hydrodynamical models

Turbulent disk without planet

Giant planet at 5 AU

W Lyra 2009
3D hydrodynamical Models

Hydrostatic modeling (Radiative transfer, chemistry)

Spectral synthesis - SEDs, detailed spectra
3D model

Hydrostatic disk structure

\[ \frac{c_T^2}{r^2} \frac{dP}{dz} = -\frac{zGM_*}{(r^2 + z^2)^{3/2}} \]

\[ \sum(r) = 2 \int_0^{z_{\text{max}}(r)} \rho(r, z) \, dz \]

3D Radiative transfer (dust continuum)

\[ \frac{dI}{d\tau_\nu} = S_\nu - I_\nu \]

\[ \int \kappa_\nu^{\text{abs}} B_\nu(T_d) \, d\nu - \int \kappa_\nu^{\text{abs}} J_\nu \, d\nu - \Gamma_{\text{dust}} = 0 \]

\[ J_\nu(r_0) = \frac{1}{4\pi} \left( I(r_0, 0, 0) \Omega_* + \sum_{i=1}^{N_\theta \cdot N_\phi} I_\nu(r_0, \theta_i, \phi_i) \Omega_i \right) \]

Dust temperatures
Intensities
10-20% of rays are suitable for short-characteristic solver.
3D model

Chemistry

\[
\frac{dn_i}{dt} = \sum_{jkl} R_{jk \rightarrow il}(T_g) n_j n_k + \sum_{jl} (R^\text{ph}_{j \rightarrow il} + R^\text{cr}_{k \rightarrow il}) n_j - n_i \left( \sum_{jkl} R_{il \rightarrow jk} n_l + \sum_{i} \left( R^\text{ph}_{i \rightarrow jk} + R^\text{cr}_{i \rightarrow jk} \right) \right)
\]

\[ p - \sum_i n_i (1 + z_i) kT_g = 0 \]

Gas thermal balance

\[
\frac{de}{dt} = \sum_k \Gamma_k(T_g, n_{sp}) - \sum_k \Lambda_k(T_g, n_{sp})
\]

Gas temperature

\[
\rho = n_e m_e + \sum_i n_i m_i
\]

\[
p = \left( n_e + \sum_i n_i \right) kT_g
\]

\[
c^2_T = \frac{p}{\rho}
\]

Obtain structure for next iteration
3D model

Chemistry

\[
\frac{dn_i}{dt} = \sum_{jkl} R_{jk\rightarrow il}(T_g)n_jn_k + \sum_{jl} \left( R_{j\rightarrow il}^{ph} + R_{k\rightarrow il}^{cr} \right) n_j - n_i \left( \sum_{jkl} R_{il\rightarrow jk}n_l + \sum_{jk} \left( R_{i\rightarrow jk}^{ph} + R_{i\rightarrow jk}^{cr} \right) \right)
\]

\[
p - \sum_i n_i(1 + z_i)kT_g = 0
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Gas thermal balance

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Gas temperature

Obtain structure for next iteration

\[
\rho = n_e m_e + \sum_i n_i m_i
\]

\[
p = \left( n_e + \sum_i n_i \right) kT_g
\]

\[
c_T^2 = p/\rho
\]
2D+3D model

Hydrostatic disk structure

Radiative transfer (dust continuum)

Gas thermal balance

Chemistry

Dust temperatures
Intensities

Obtain structure for next iteration

Gas temperature

\[ \frac{c_s^2}{\rho} \frac{dP}{dz} = -\frac{zGM_\star}{(r^2 + z^2)^{3/2}} \]

\[ \sum(r) = 2 \int_0^{\text{max}(r)} \rho(r, z) dz \]

\[ \frac{dT}{d\tau_v} = S_v - I_v \]

\[ \int \kappa_v \alpha B_\nu(T_d) d\nu - \int \kappa_v \alpha J_v d\nu - \Gamma_{\text{dust}} = 0 \]

\[ J_v(r_0) = \frac{1}{4\pi} \left( I_v(r_0, 0, 0) \Omega + \sum_{i=1}^{n} I_v(r_0, \theta, 0) \Omega \right) \]

\[ \rho = n_e m_e + \sum_i n_i m_i \]

\[ n = \left( n_e + \sum_i n_i \right) kT_g \]

\[ c_s^2 = p/\rho \]
Resulting $T_{\text{gas}}$ for one azimuth

Obs-$z/r$ on $y$-axis

Linear $z$
3D hydrodynamical Models

Hydrostatic modeling (Radiative transfer, chemistry)

Spectral synthesis - SEDs, detailed spectra
Spectral Energy Distribution

(T-tauri star)
Spectral Energy distributions

Regály et al, 2012

Ovelar et al, 2013
Questions?