1D and 3D radiative transfer in protoplanetary disks

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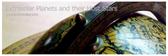

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Motivation

Why modelling protoplanetary disks?

- we need to know disk structure to understand planet formation
- structure can be investigated by means of high-resolution IR spectroscopy
- look at inner disk region (where many exoplanets are observed) & use detailed model spectra

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Why a new radiative transfer code?

- there are several structure and radiative transfer codes for protoplanetary disks (e. g. D'Alessio et al. 1998, Dullemond & Dominik 2004)
- use different approach: use stellar atmosphere code `PHOENIX` which can handle extensive lists of atomic and molecular lines as well as dust; adopt it to disks (geometry, heating sources)
- model detailed and self-consistent 1D disk structures
- expect that our line radiative transfer calculations can provide new insight about inner disk structure

1D radiative transfer: Basics

- assume standard accretion disk model for geometrically thin disks $H \ll R$ (Shakura & Syunyaev 1973, Lynden-Bell & Pringle 1974) $\Rightarrow$ parametrize viscosity $\Rightarrow$ decouple vertical and radial structure
- separate disk in rings and calculate vertical structure and RT for each ring assuming physics does not change over ring width

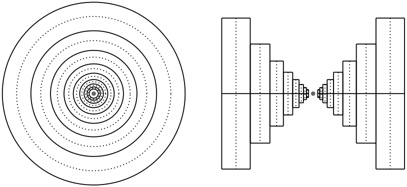

Figure: Disk ring structure as adopted for our calculations. The radius of the rings increases exponentially.

Input parameters

central star properties:	$M_\star$, $R_\star$, T_{eff}
radius of disk ring:	R
mass accretion rate:	$\dot{M}$
Reynolds number:	Re (sets viscosity: $\bar{\nu} = \sqrt{GM_\star R}/Re$; $Re \propto \alpha^{-1}$)

1D radiative transfer: Model basics

Hydrostatic equilibrium:

unlike classical stellar atmosphere problem, gravity g is function of height z

$$\frac{dP}{dm} = \frac{GM_\star}{R^3} z \tag{1}$$

Radiative transfer:

solve the radiative transfer equation for a given number of quadrature points μ_i

$$\mu_i \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu \tag{2}$$

with boundary conditions

$$I_\nu(-\mu, z_{\max}) = I_\nu^{\text{ext}}(-\mu, z_{\max}) \quad \text{and} \quad I(-\mu, 0) = I(\mu, 0)$$

Radiative equilibrium:

radiative energy has to balance dissipated mechanical energy

$$E_{\text{mech}} = E_{\text{rad}} \iff \frac{9}{4}\frac{GM_\star}{R^3}\nu\rho = 4\pi \int_0^\infty (\eta_\nu - \chi_\nu J_\nu)\, d\nu \tag{3}$$

1D radiative transfer: Dust treatment & irradiation

dust formation

- condensate formation treated by assuming chemical and phase equilibrium for several hundred species (Dusty setup; Allard et al. 2001)
- grain opacities calculated for 50 most important refractory condensates (for which optical data is available)
- absorption and scattering using Mie formalism

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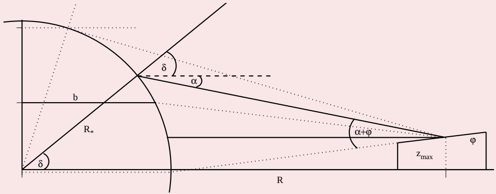
irradiation geometry

- blackbody or `PHOENIX` spectrum as input
- determine corresponding star surface fraction for each quadrature point μ_i



Analysis of GQ Lup

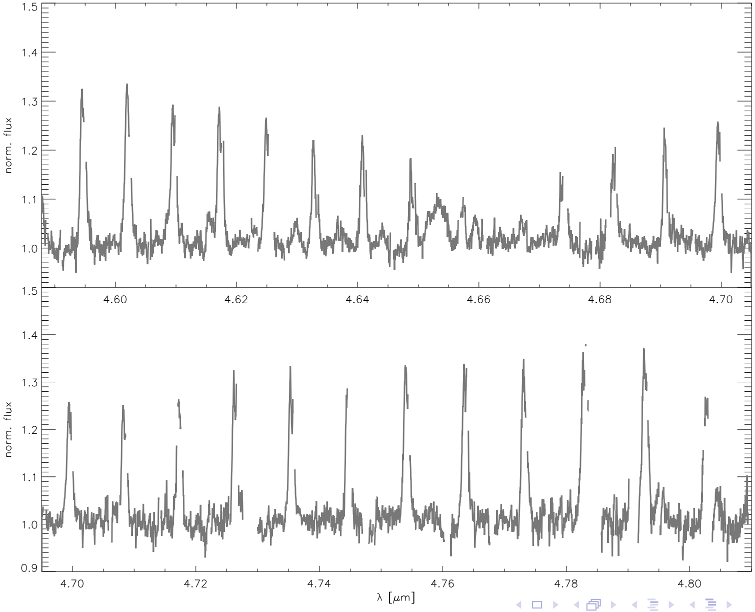
- GQ Lup is a classical T Tauri star (CTTS) with a lately discovered sub-stellar companion GQ Lup B (Neuhäuser et al. 2005)
- very active: more than 2 mag variability ($V_{\max} = 11.33$ mag and $V_{\min} = 13.36$ mag)
- Broeg et al. (2007) and Seperuelo Duarte et al. (2008) derive different parameters from lightcurves (orbital period) and spectroscopy (rotational period $v \sin i$)

authors	d [pc]	P [d]	$v \sin i$ [km s^{-1}]	$R_\star$ [$R_\odot$]	incl. [°]
Broeg et al.	140	8.45	6.8	2.55	27
Seperuelo D. et al.	150	10.7	6.5	1.80	51

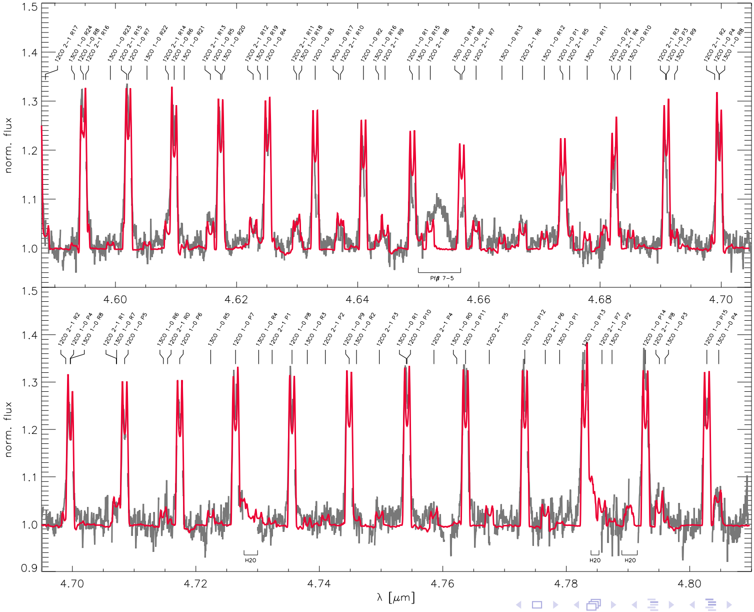
calculated sets of disk ring structures/spectra

$$R = 0.031\ \mathrm{AU} - 0.422\ \mathrm{AU}$$
$$T_{\mathrm{eff}} = 4060\ \mathrm{K}$$
$$M_\star = 0.8\ M_\odot$$
$$\dot{M} = 2 \cdot 10^{-8}\ M_\odot/\mathrm{yr} - 7 \cdot 10^{-10}\ M_\odot/\mathrm{yr}$$
$$Re = 1/5 \cdot 10^{4}\ (\alpha \sim 0.05)$$

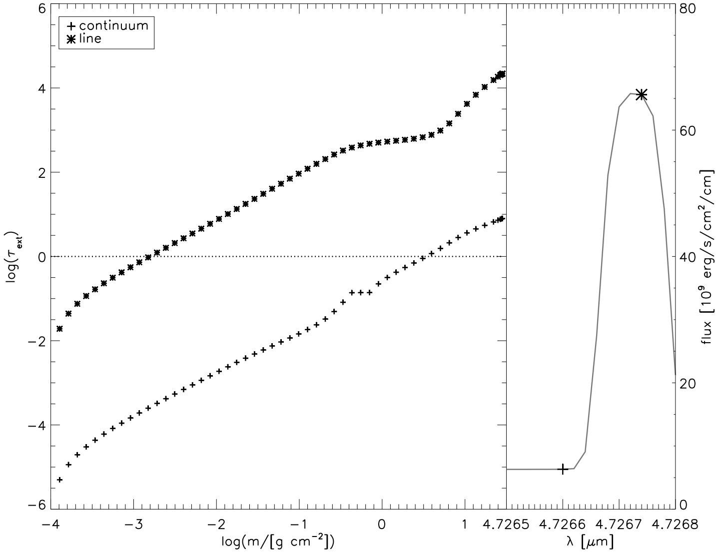
Model fit


1.5
1.4
1.3
1.2
1.1
1.0
norm. flux
4.60
4.62
4.64
4.66
4.68
4.70
1.5
1.4
1.3
1.2
1.1
1.0
0.9
norm. flux
4.70
4.72
4.74
4.76
4.78
4.80
λ [μm]

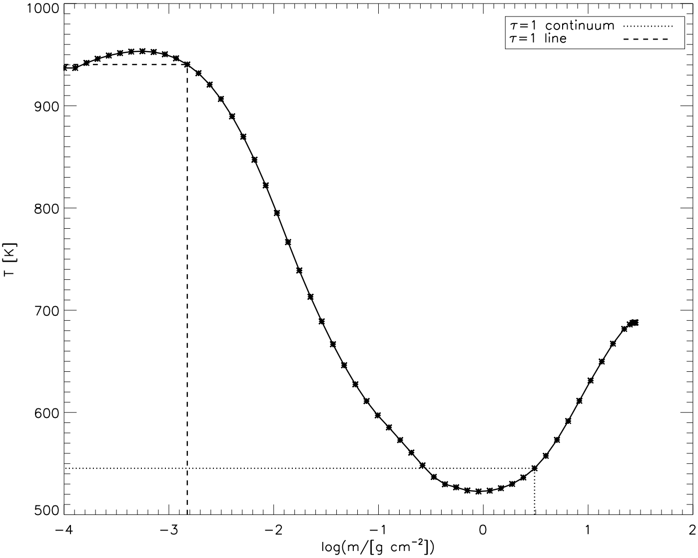
Model fit


norm. flux
norm. flux
1.5
1.4
1.3
1.2
1.1
1.0
0.9
4.60
4.62
4.64
4.66
4.68
4.70
4.72
4.74
4.76
4.78
4.80
Pfβ 7–5
H2O
H2O
H2O
λ [μm]

Line origin


continuum
line
$\log(\tau_{ext})$
$\log(m/[g\ cm^{-2}])$
$\lambda\ [\mu m]$
flux [10^9 erg/s/cm^2/cm]
6
4
2
0
−2
−4
−6
−4
−3
−2
−1
0
1
4.7265
4.7266
4.7267
4.7268
80
60
40
20
0

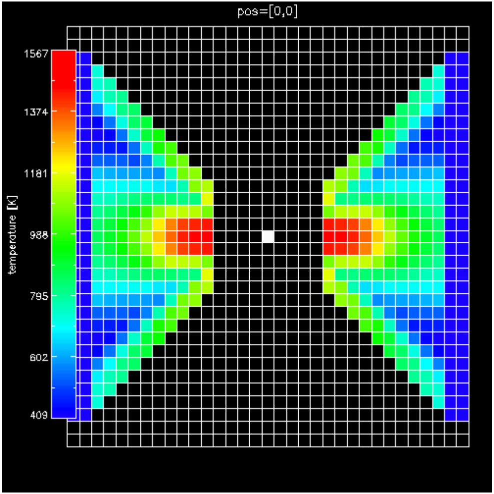
Line origin



1000
900
800
700
600
500
T [K]
−4
−3
−2
−1
0
1
2
log(m/[g cm^{-2}])
τ=1 continuum
τ=1 line

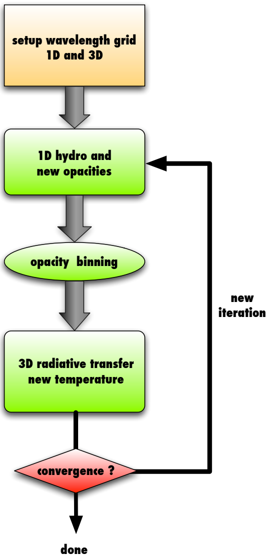
3D radiative transfer: Basics

- use 3D radiative transfer framework of Hauschildt & Baron (2006)
- 1D models (temperature, opacity) are interpolated on 3D grid (Cartesian now, cylindrical soon)
- typical size $65 \times 65 \times 65$ voxels and 64^2 angles
- simple 2-level model atom line transfer in moving media implemented
- accelerated lambda iteration can be used to include scattering in RT



Coupling between stellar irradiation and disk structure

- in 1D case only disk surface is irradiated by central star
- in reality star light irradiates inner disk wall $\Rightarrow$ puffed-up inner rim?
- 1D opacity sampling of $\approx 10^5$ frequencies $\Rightarrow$ use Planck mean opacities for 3D RT with ≈ 50 frequencies



Acknowledgements/References

Acknowledgements

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