Molecular Line Radiative Transfer in Protoplanetary Disks

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Goal of this project is to analyze the line radiative transfer (LRT) in protoplanetary disks and to compare several approximate LRT methods with Monte Carlo calculations

Disk Model

A flaring steady-state model of a Class II disk with vertical temperature gradient from D'Alessio et al. 1999 (see Fig.1)

Star Radius: $2.64 R_{sun}$
Star Mass: $0.7 M_{sun}$
Star Temperature: 400[illegible]

Disk radius: 800 AU,
Disk mass: $0.07 M_{sun}$,
Accretion rate: $10^{-8}\ M_{sun}\,yr^{-1}$
Turbulent velocity: 0.1 km/s
Keplerian rotation

Uniform and layered molecular abundances
CO, CS, HCO^+, HCN and H_2CO

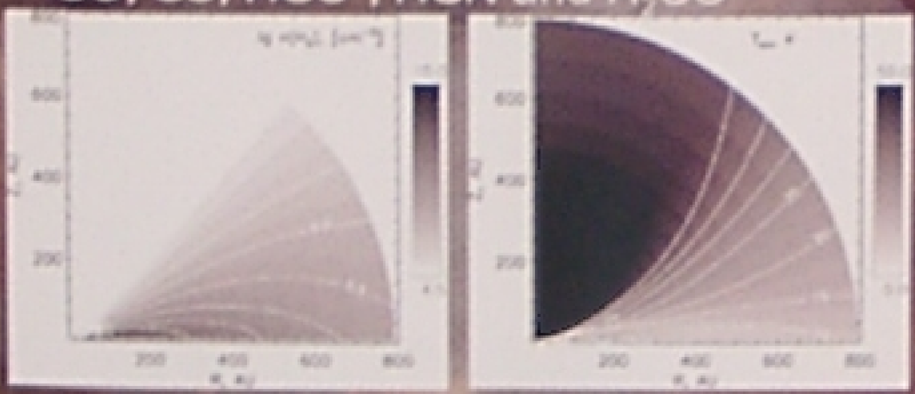

Fig. 1: Density and temperature distributions in the adopted disk model

Exact Method

2D non-LTE code „ART" (part of „URANIA" package)

[illegible]mmetry and spherical [illegible]ate system

Accelerated Λ-iterations

Long characteristics with Monte Carlo ray sampling

New acceleration concepts of interacting cells (see Fig.2)

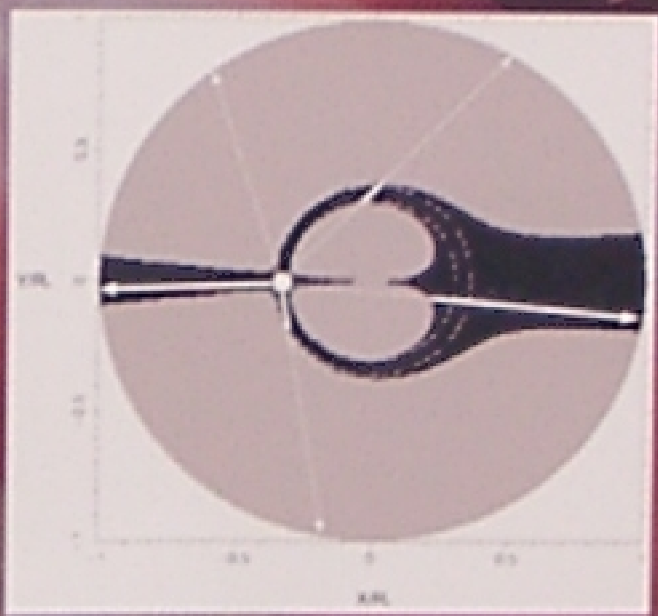

Fig. 2: Black area represents the disk cells that are radiatively coupled to the white dot in the equatorial plane of the Keplerian disk

Approximate Methods

1) LTE: Local Thermodynamical Equlibrium

2) FEP: Full Escape Probability (optically thin approximation)

3) LVG: Large Velocity Gradient (the photons are assumed to escape in equatorial plane only)

4) VEP: Vertical Escape Probability (the photons are assumed to escape in vertical direction only)

5) VOR: Vertical One Ray (non-local 1D method for vertical direction)

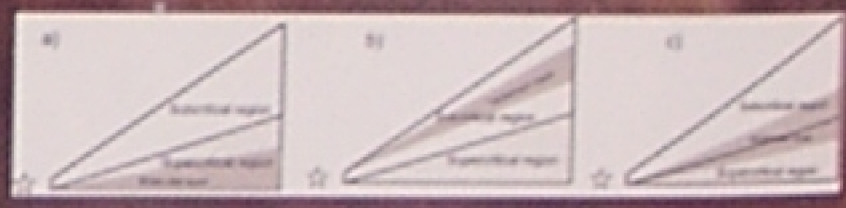

Fig. 3: Three distinct cases of the line excitation in protoplanetary disk with layered chemical structure. Depending on location of molecules, the rotational transitions can be thermally, sub-thermally, or super-thermally excited.

Results

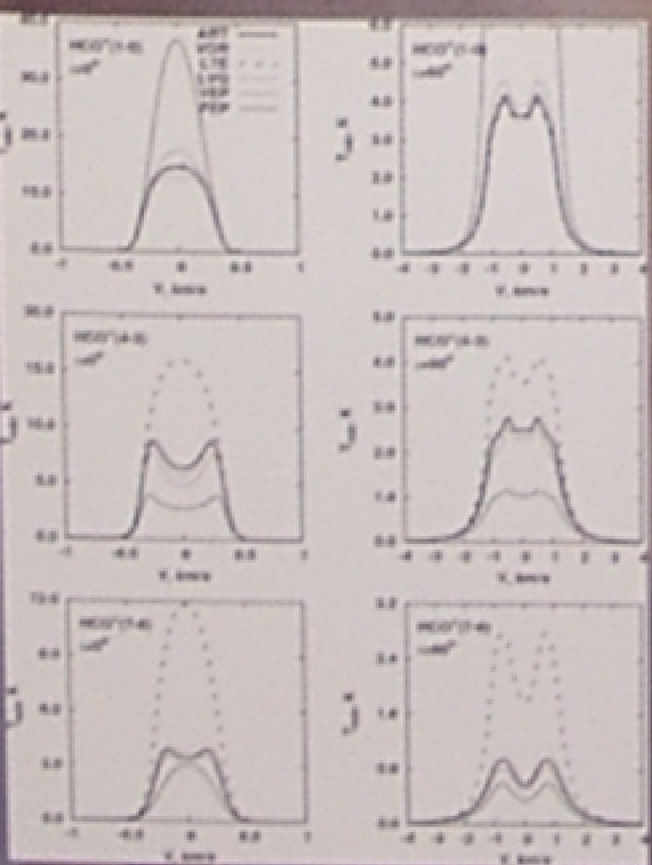

Fig. 4: HCO^+ synthetic spectra obtained by different LRT methods for the disk model with uniform abundances. The spectra are convolved with 10'' beam, the distance is 140 pc. The disk inclination is 0° (left panels) and 60° (right panels)

1) LTE approach is appropriate for low molecular transitions only;

2) FEP can be used for the upper transitions (beware of the maser effect for low transitions!);

3) LTE and FEP work well for chemically stratified disks (molecules are in the warm intermediate layer);

4) LTE and FEP are not always accurate for chemically uniform disks;

5) LVG and VEP are in general more reliable methods than FEP and LTE;

6) VOR method is comparable to LVG but slower;

7) Various regimes of the line excitation and radiative coupling in protoplanetary disks are analyzed;

8) Ray-tracing part of the Monte-Carlo LRT method can be accelerated for rotating disks by factors of 10–50 when only radiatively coupled disk zones are taken into account.

Fig. 5: HCO^+(4-3) intensity map for the 0.68 km/s velocity offset and for the disk inclination of 60°. The uniform (top row) and layered (bottom row) abundances of HCO^+ are utilized. The results are obtained by LTE (left), ART (middle), and FEP (right panel) methods.

Literature

1) Pavlyuchenkov et al. (2007), ApJ, submitted; 2) van Zadelhoff et al. (2001), A&A, 377, 566; 3) Guilloteau & Dutrey (1998), A&A, 339, 467