Tracing planet-induced structures using molecular lines

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1. Introduction

Protostellar disks are considered as the birthplace of planets. Structures like spiral arms, gaps and cavities are suggested indicators of planet-disk interaction. We investigate the feasibility to use molecular lines to trace planet-induced structures in circumstellar disks. Based on hydrodynamic simulations of planet-disk interaction obtained with the PLUTO code, we perform self-consistent temperature calculations and produce molecular line velocity-channel maps and spectra of these disks using our new N-LTE line radiative transfer code **Mol3d**.
Subsequently, we simulate ALMA observations using the CASA simulator.

2. Non-LTE line radiative transport code Mol3d

We developed a new Non-LTE continuum and line radiative transport (**RT**) code called **Mol3d**. This code is originally based on the RT code **MC3D** (Wolf et al., 1999; Wolf, 2003).
Mol3d features self-consistent dust temperature calculation and dust re-emission maps/SED's calculation. It has been designed with the motivation to create a very fast and flexible code which can easily be extended. For the molecular lines, level populations can be calculated using three different approximation methods: Large velocity gradient (**LVG**), free escape probability (**FEP**) and the local thermodynamical equilibrium (**LTE**) assumption. Einstein coefficients and collision rates are taken from the publicly available Leiden Atomic and Molecular Database **LAMDA** (Schöier et al., 2005). A comparison between all three methods is shown in **Figure 1**:

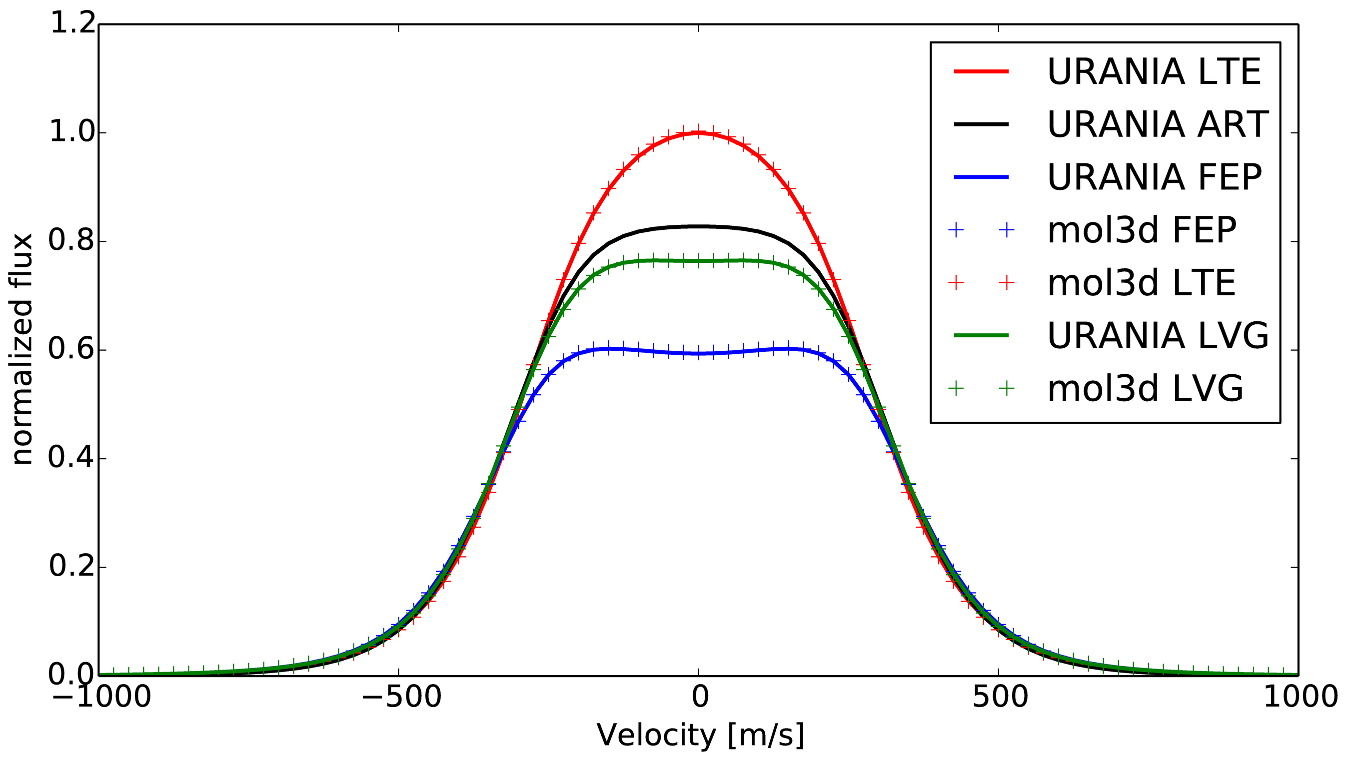

Figure 1: HCO^+ 3-2 spectrum of a typical protoplanetary disk viewed *face-on*. Solid lines show spectra obtained with the URAN(IA)-package (Pavlyuchenkov & Shustov, 2004) while dotted lines show the corresponding spectra obtained with Mol3d. Color-coded are different methods. **LVG** method is just in between **FEP** and **LTE** solution and very comparable to the spectrum obtained with an accelerated Monte-Carlo (**ART**) method.

After the level-populations have been calculated, velocity-channel maps and spectra can be obtained using a ray-tracing algorithm. We decided to solve the RT equation using a Runge-Kutta method of order 4(5) with automatic step control, which allows us to control the maximum integration error.
Finally, the code is fully parallelized using **OpenMP** and scales nearly linear on a CPU using 16 cores.

3. Hydrodynamic simulations & Parameter space

We investigate the feasibility to trace a Jupiter-mass planet in the outer regions of a circumstellar disk around a TTauri star. The underlying density distribution is the result of hydrodynamic simulations by Uribe et al. (2011). Please note that the surface of the disk has nearly the same density as in the undisturbed case.

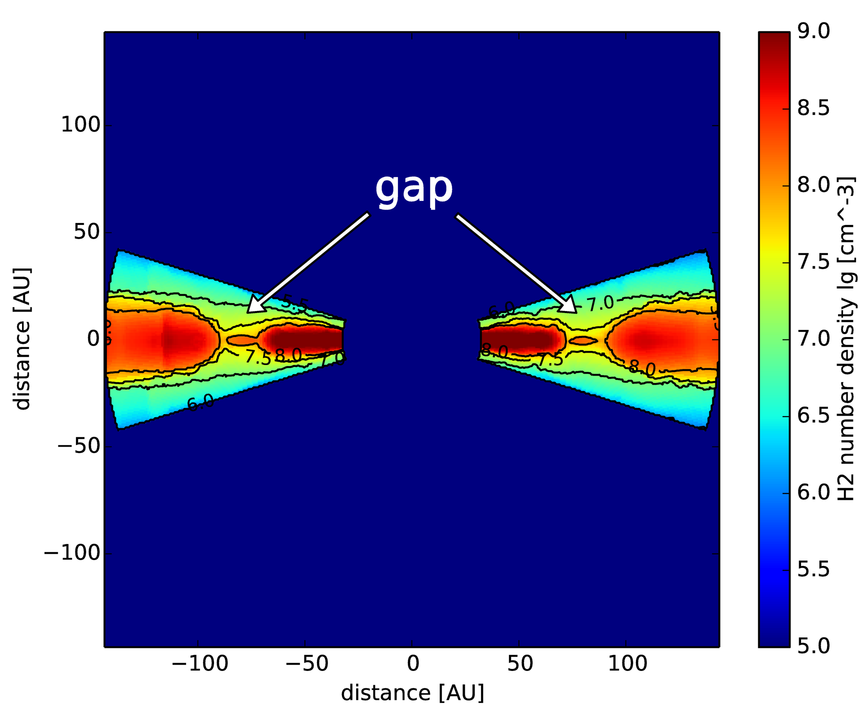

Figure 2: Density distribution perpendicular to the disk midplane. A planet with a mass of 10^{-3} stellar masses is located at 80 AU.

parameter	value(s)
M_{disk} [$M_\odot$]	$2.67 \cdot 10^{-1}$,...,10^{-7}
R_{in} [AU]	14 - 50
R_{out} [AU]	63 - 225
T_{star} [K]	4000, 9500
R_{star} [$R_\odot$]	2, 2.48
M_{star} [$M_\odot$]	0.7
L_{star} [$L_\odot$]	0.92, 45
molecule	CO 3-2, HCO^+ 4-3
abundance [N(X)/N(H2)]	10^{-4},10^{-8}

Figure 3: Explored parameter space for this study. We consider two near *face-on* inclinations, six disk masses, seven disk radii, and two different typical pre-main-sequence host stars (TTauri, Herbig AE) in a distance of 140 pc. We calculate up to 141 individual CO 3-2 and HCO^+ 4-3 velocity-channel maps to investigate the frequency dependence of the structures indicated above.

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The author of this poster is around and happy to answer any emerging question!
Florian Ober

4. ALMA predictions

After calculating ideal velocity-channel maps, we use the CASA (v4.2) simulator to produce realistic ALMA observables for 5 different configurations, width maximum baselines from 0.7 km - 16.3 km and an observing time of 2 hours:

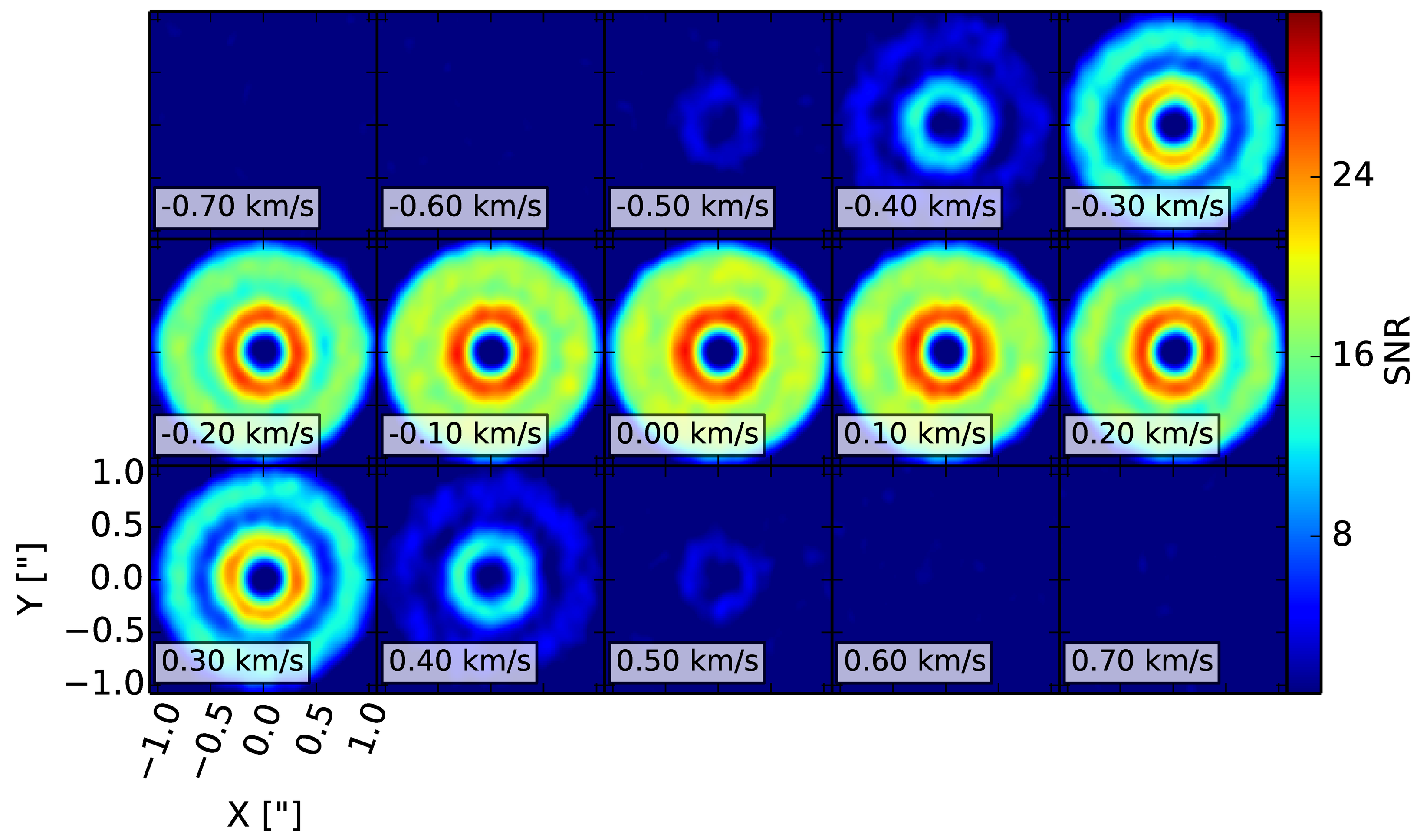

Figure 4: CO 3-2 velocity-channel map for an exemplary model of our parameter set as it could be observed with ALMA using configuration 14 (maximum baseline: 1.6 km). The disk is seen *face-on*. Thus, the line width is given only by the thermal- and microturbulent-velocities (here $\approx 100 - 200$ m/s). Consequently the gap appears as a symmetric ring. We find that the best contrast between gap and disk is not necessarily at the lines center. Due to the optical thickness of the line the optimum velocity-channel varies with disk mass.

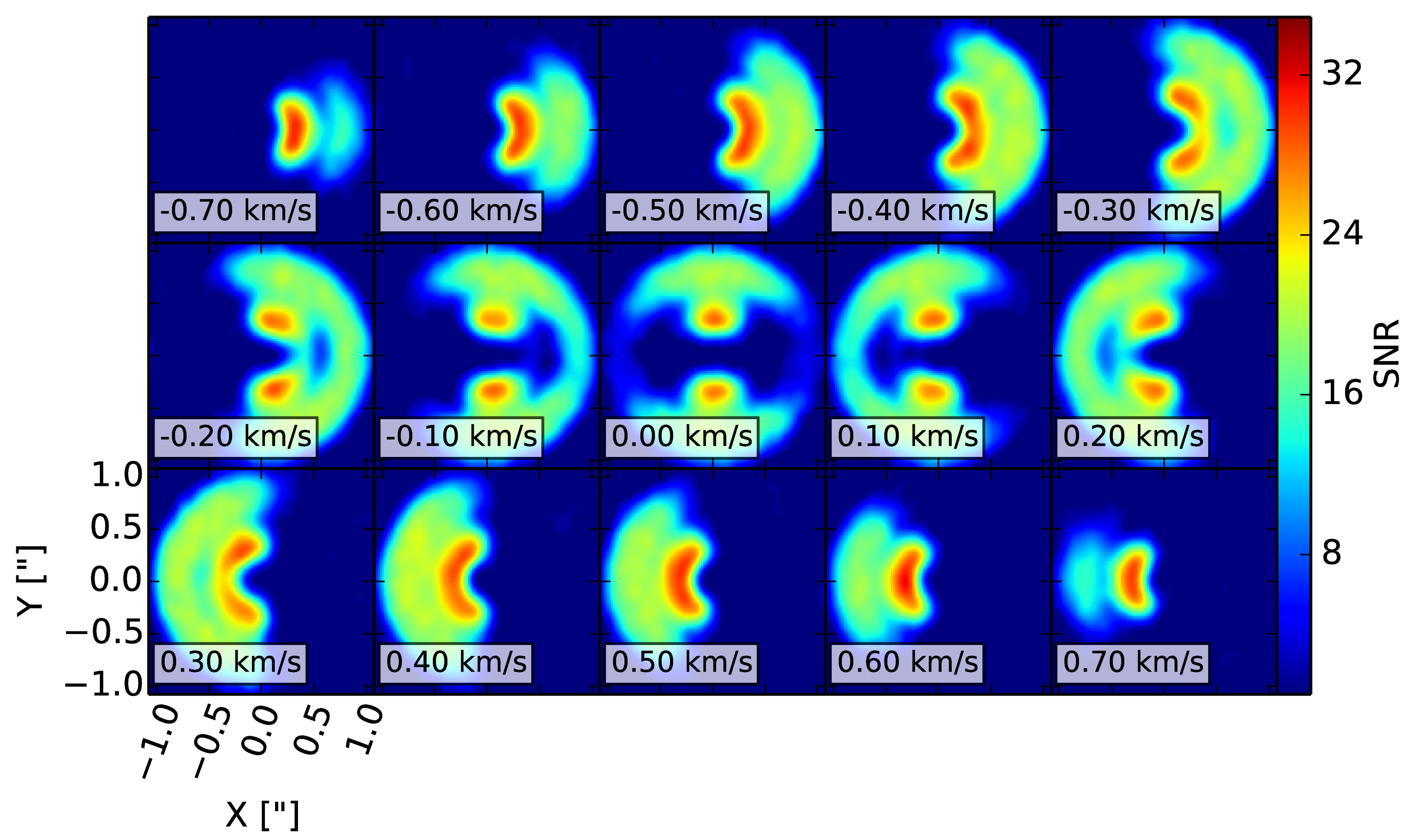

Figure 5: The same model as above but now with a disk inclination of 10°. Positive velocities indicate parts of the disk moving away from the observer (red-shifted) while negative velocities belong to parts of the disk moving towards the observer (blue-shifted). In contrast to the *face-on* disk, the different parts of the disk can be observed at different velocities. Thus, the gap does **not** appear as a symmetric ring in the velocity-channel maps but is hidden in a complex pattern which prevents simple gap detection.

5. Results

We find that the major fraction of protoplanetary disks in our parameter space could be detected in the considered molecular lines. Unlike the continuum case, gap detection is not straightforward in lines as the individual velocity-channel maps reveal complex asymmetric pattern. However, by comparing with simulated observations of undisturbed disks we are able to identify specific regions in the velocity-channel maps, which are most characteristic for planet-induced structures.

Our simulations of high-angular resolution molecular line observation demonstrate the potential of ALMA to detect gaps in young circumstellar disks. These results will significantly improve our understanding of the physical and chemical environment in which planets form.

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