# Molecular line radiation from turbulent clouds

**V. Ossenkopf[1], R. Klessen[2], F. Heitsch[3]**

[1] 1. Physikalisches Institut der Universität zu Köln; [2] Astrophysikalisches Institut Potsdam; [3] JILA, University of Colorado at Boulder

## Motivation

Recent simulations of compressible hydrodynamic or magnetohydrodynamic turbulence provide first realistic models for the structure of molecular clouds (Padoan et al. 1998, Mac Low et al. 1998, Stone et al. 1998). For a systematic comparison between observations and turbulence simulations the radiative transfer problem has to be solved, translating the density, temperature, and velocity structure into maps of molecular line profiles.

The fully self-consistent approach by Juvela (1997) is computationally very demanding and not suited to evaluate a large set of cloud models. For a systematic comparison between numerous models and observations we developed a new efficient radiative transfer algorithm. By studying how the properties of the turbulence simulations are reflected in the resulting molecular line maps, we give rough guidelines how to deduce the true structure of molecular clouds from molecular line observations.

## The line radiative transfer problem

To compute the line intensities $I_{\rm ul}(\vec{r},\nu)$ observable from a cloud model, the radiative transfer problem has to be solved.

$$\vec{n}\cdot\mathrm{grad}\,I_{ul} = -\kappa_{ul}I_{ul} + \epsilon_{ul}$$

$$\kappa_{ul} = \frac{h\nu_{ul}}{c}\left[n_l B_{lu} - n_u B_{ul}\right]\,\Phi(\nu)$$

$$\epsilon_{ul} = \frac{h\nu_{ul}}{c}\,n_u A_{ul}\,\Phi(\nu)$$

$$n_i\left(\sum_{i<l}A_{ij} + \sum_{j\neq i}B_{ij}u_{ij} + \sum_{j\neq i}C_{ij}\right) = \sum_{j>i}A_{ji}n_j + \sum_{j\neq i}B_{ji}u_{ij}n_j + \sum_{j\neq i}C_{ji}n_j$$

$$u_{ul} = \frac{1}{c}\int_{4\pi}d\vec{n}\int_0^\infty d\nu\,\Phi(\nu)\,I_{ul}$$

The full line radiative transfer problem is a system of integro-differential equations coupling the intensity $I_{\rm ul}(\vec{n},\vec{r},\nu)$ to the molecular level populations $n_i(\vec{r})$.

As all quantities depend on the location $\vec{r}$, the direction $\vec{n}$, the transition $ul$, and frequency $\nu$ we obtain a 7-dimensional problem

## The two-scale approximation for turbulent clouds

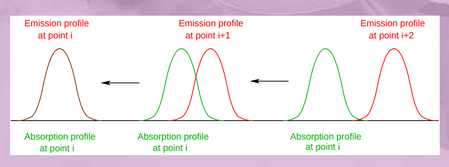
### Background

- Fully selfconsistent 3-D radiative transfer computations with a low resolution take days on a supercomputer (Juvela 1997, Padoan et al. 2000).
- Molecular line observations have typical calibration errors of 20 %.

The three-dimensional radiative transfer code introduced by Ossenkopf (2002) uses a combination of two sophisticated approximations to solve the excitation problem:

### Local LVG approximation with density gradients

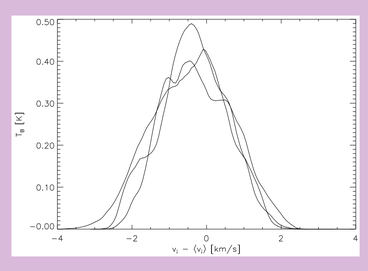
In turbulent molecular clouds the line-of-sight velocity in each direction is changed by more than the thermal line width on the scale of a few pixels.




Remote points are radiatively decoupled. The local radiative transfer problem can be solved using local quantities only (Ossenkopf 1997).

### The average isotropic field approximation

- Remote points obtain with a certain probability the same line-of-sight velocity again.
- The turbulent medium is isotropic on a large scales.
- Only the integral over all directions and frequencies enters the radiative excitation.




Average $^{13}$CO 2–1 line profiles in three perpendicular directions for a large-scale driven hydrodynamic model.

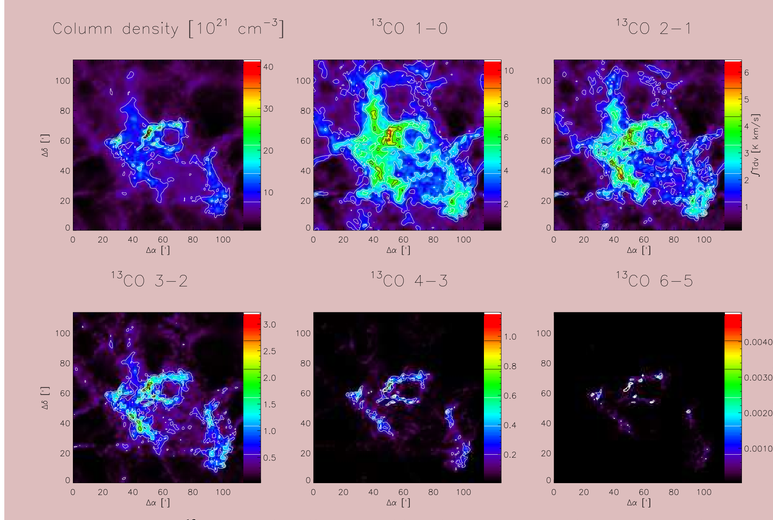
The long-range radiative interaction can be treated by an average isotropic line profile added as external radiation to the local LVG approximation.

### Computation of line profiles

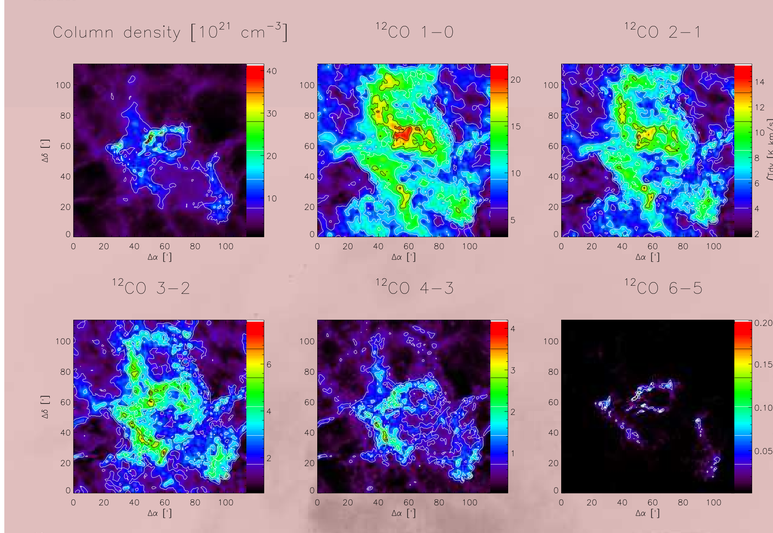
- With the excitation from the two-scale approximation, the radiative transfer equation can be integrated.
- Beam convolution
- Additional noise

## Results

Molecular line maps were computed for a large number of different isothermal turbulence simulations for various molecules and transitions:




Column density and $^{13}$CO maps in different transitions for a large-scale driven hydrodynamic turbulence model

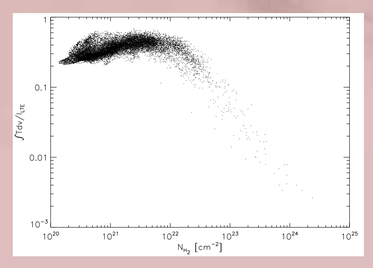



$^{12}$CO maps in the equivalent transitions computed for the same turbulence model

No single transition provides a good reproduction of the underlying column density structure. The lower transitions of CO isotopes always trace the extended gas whereas the higher transitions reflect only dense shocked or collapsing filaments.

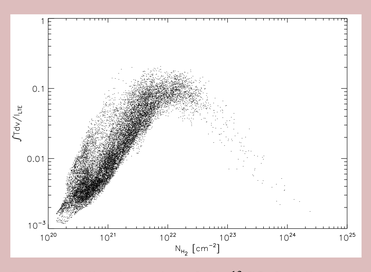
### Tracing the column density in molecular lines ?

Integrated CO intensities are often used to measure the cloud column density (Meyerdierks & Heithausen 1996). We have tested this approach by comparing the known structure of the cloud models with resulting line intensities.

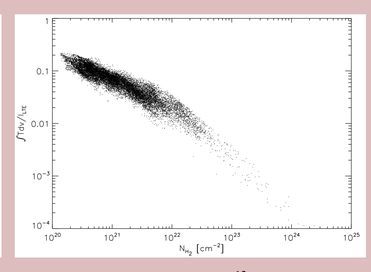



Integrated line intensity of the $^{13}$CO 1–0 line relative to the line-of-sight integrated LTE emissivity as a function of the column density in a collapsing large-scale turbulence model.

In a density range covering two orders of magnitude the $^{13}$CO 1–0 line shows an almost constant factor translating the column density into the integrated line intensity. Thus the line is often a good density tracer, but this density range is still very limited. Other molecules and other transitions show in general much smaller ranges with a constant translation factor:




Integrated line intensity of the $^{13}$CO 3–2 line relative to the LTE intensity for the same model.

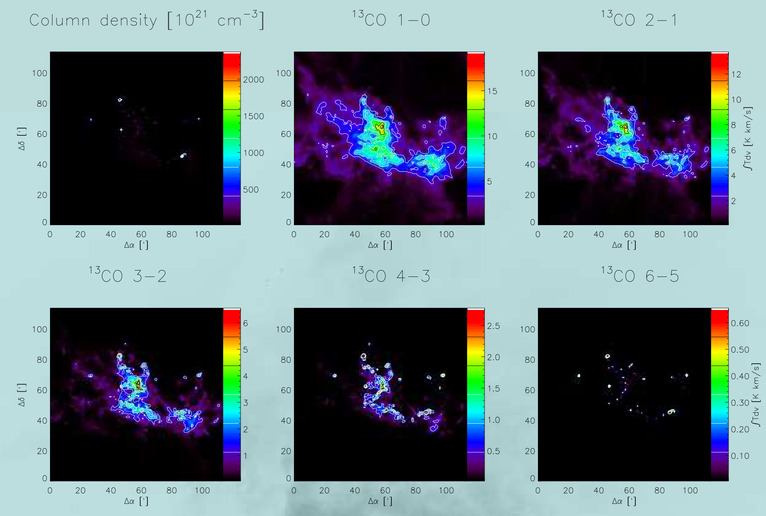



Integrated line intensity of the $^{12}$CO 1–0 line relative to the LTE intensity for the same model.

- For each transition, we find only a limited density range where the molecular line emission is a good tracer of the total column density.
- Only in few models and a narrow density range $^{12}$CO and $^{13}$CO are both good tracers of the column density.
- Averaged over some density range by a large telescope beam the lines also appear to have a constant intensity per column density.

## Gravitational collapse in molecular lines

We followed the gravitational collapse in the turbulence simulations computing the observable line profiles for each time step. The figure demonstrates the maps after one free-falling time when 28% of the total gas mass has turned into protostellar cores.




Column density map and $^{13}$CO maps in different transitions for the turbulence model shown on the left after one free-falling time of gravitational collapse.

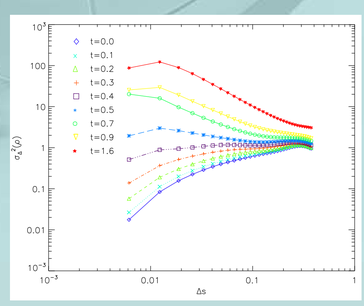
All molecular line maps still look similar to the maps before gravitational collapse, although the column density structure has drastically changed.

### The structure evolution in the Δ-variance

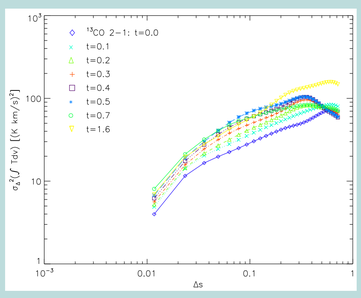
The Δ-variance (Stutzki et al. 1998) is a measure for the relative amount of structure on a certain size scale. Its spectrum shows the spatial scaling behavior of any measured quantity.

#### The density structure:

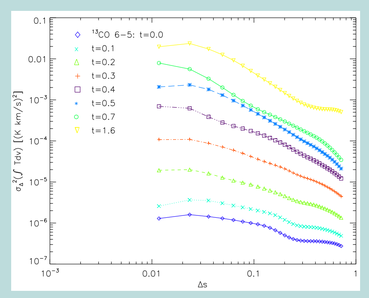
Evolution of the Δ-variance spectra of the column density maps during the gravitational collapse. Initially the cloud is dominated by large scale structure (positive slope of the Δ-variance). As star-formation proceeds, more and more structure is created on small scales in the form of protostellar cores leading to an overall negative slope of the Δ-variance.




#### Molecular lines:




Evolution of the Δ-variance spectra of the corresponding $^{13}$CO 2–1 maps during the collaps

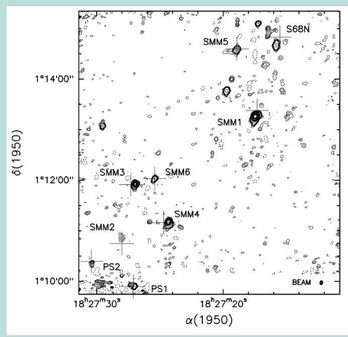



Evolution of the Δ-variance spectra of the corresponding $^{13}$CO 6–5 maps

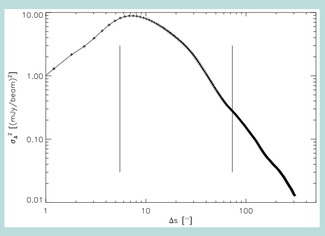
The protostellar collapse hardly modifies the slope of the Δ-variance in the molecular line maps. It is very difficult to infer the formation of dense cores from molecular lines.

## Comparison with observations

As molecular line observations do not reflect the complete density structure of clouds with ongoing star-formation, dust continuum observations are a more promising tool. We have compared dust observations of a star-forming region with the collapse simulations discussed above.




OVRO 3mm continuum map of a star-forming region in Serpens from Testi & Sargent (1998)




Δ-variance spectrum of the Serpens continuum map. The two vertical lines represent the limits of the significant size range in the observation.

In dust continuum maps, the formation of protostellar cores appears in quantitative agreement with the structural signature of the gravitational collapse in the turbulence models.

## Conclusions

- Several tracers have to be observed to provide any conclusion on the cloud structure.
- No single molecular transition can follow the gravitational collapse. The measured structure is dominated by the critical density of the transition, not by the full density distribution of the cloud.
- Typical CO observations only provide information on the large-scale distribution of low density gas, which is well recovered even from optically thick lines.
- Maps of the dust emission or extinction are a better tracer of the overall density structure than molecular lines.
- The information from the line profiles is, however, essential to resolve the velocity structure.
- The deduction of column densities from line intensities applying a constant conversion factor will necessarily fail outside of a limited density range. The molecular line transfer „hides“ all material outside of a certain density range either by subthermal excitation or by saturation.

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