*Galactic Star Formation Across the Stellar Mass Spectrum*
*ASP Conference Series, 2002*

# Observing turbulent fragmentation in molecular clouds

Volker Ossenkopf

*SRON National Institute for Space Research, P.O. Box 800, 9700 AV Groningen, the Netherlands*
*I. Physikalisches Institut der Universität zu Köln, Zülpicher Straße 77, 50937 Köln, Germany*

**Abstract.** The process of molecular cloud fragmentation, leading to the formation of collapsing dense cores, is still poorly understood. Turbulence simulations provide a promising approach to learn about the structuring processes. To compare them with observations it is necessary to solve the radiative transfer problem and to characterise the structures by statistical measures. The development of corresponding methods and their application to recent cloud simulations discriminates which information can be derived from molecular line observations and which models match the observational data.

## 1. Introduction

Observations of the interstellar medium show an irregular, filamentary, and often fractal structure. This structure extends over many orders of magnitude in size and density scale from protostellar fragments to giant molecular clouds. The dynamical behaviour and evolution of the clouds is not determined by processes on single scales. The density and velocity structure on all length scales is interconnected, so that turbulent processes on a large scale may modify the formation of protostellar cores on the small scale (Williams et al. 1999). A combined study of the structure of the interstellar medium covering several scales is required to reveal the properties of the turbulent cascade, to identify physical processes modifying this cascade at certain length scales, and to discover the mechanism of cloud fragmentation into protostellar cores.

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, Bate 1998). Systematic comparisons between observations and the turbulence simulations are required to discriminate between these models so that the role of the different physical mechanisms included in the different simulations can be estimated. With an iterative improvement of the models to fit more and more observed properties we can finally come to a self-consistent picture of the structure evolution in molecular clouds.

However, the systematic comparison of turbulence models with molecular line observations faces two basic problems. The first one is the complexity of the radiative transfer translating the density, temperature, and velocity structure obtained from the turbulence simulations into maps of molecular line profiles.

To evaluate a large number of models an efficient radiative transfer algorithm is needed. The fully self-consistent approach by Juvela (1997) is computationally very demanding and not well suited to evaluate a large set of cloud models with high resolution. Sect. 2 summarises the properties of an alternative code approximating the solution of the radiative transfer problem with an accuracy comparable to the calibration uncertainty of typical molecular line observations.

The second problem is the comparison of the molecular lines computed from the turbulence simulations with the observed data. No simulation will provide an exact reproduction of the observed complex structures. Thus, the comparison has to rely on statistical descriptions of the data sets. To cover all structural aspects, measures for the isotropic intensity and velocity scaling behaviour, for the anisotropy in the maps, for the shape and spatial correlation of the line profiles, and for the relation between density and velocity structure have to be combined. They are discussed in Sect. 3. Sect. 4 finally summarises the results of the systematic comparisons between molecular cloud observations and selected turbulence models.

## 2. Radiative transfer computations

The three-dimensional radiative transfer code introduced by Ossenkopf (2002) uses a combination of two approximations to solve the molecular excitation problem for a given turbulence simulation. On small scales it exploits the large velocity gradients in turbulent media to limit the size of regions which interact radiatively. On large scales it uses the global isotropy of the turbulent structure to describe the interaction of distant regions with the same line-of-sight velocity by an average field. These two approximations allow for a fast computation of the molecular lines that would be observed from a simulated cloud with an accuracy of 20 % for all turbulence simulations considered here.

Fig. 1 demonstrates the results of such a computation for an isothermal hydrodynamic turbulence model. The column density map is compared with maps that would be observed in different $^{13}$CO transitions. Although $^{13}$CO is generally thought to be a good column density tracer, none of the molecular lines reveals the true density structure. For each molecule and each transition, the regime of a constant ratio between column density and molecular line brightness is restricted to a very limited density range. The systematic application of the radiative transfer program to many turbulence simulations showed that any conclusion on the structure of the interstellar medium must be based on the observation of various tracers.

## 3. Comparing observations and turbulence simulations

To compare observed maps and maps obtained from the radiative transfer code applied to the turbulence simulations, statistical methods are required. They have to go beyond traditional intensity histograms as the turbulent structure is essentially characterised by spatial scaling properties.

Bensch, Stutzki, & Ossenkopf (2001) showed that the $\Delta$-variance analysis is an excellent tool to measure the isotropic scaling behaviour of the density structure. Future extensions should include the characterisation of anisotropies

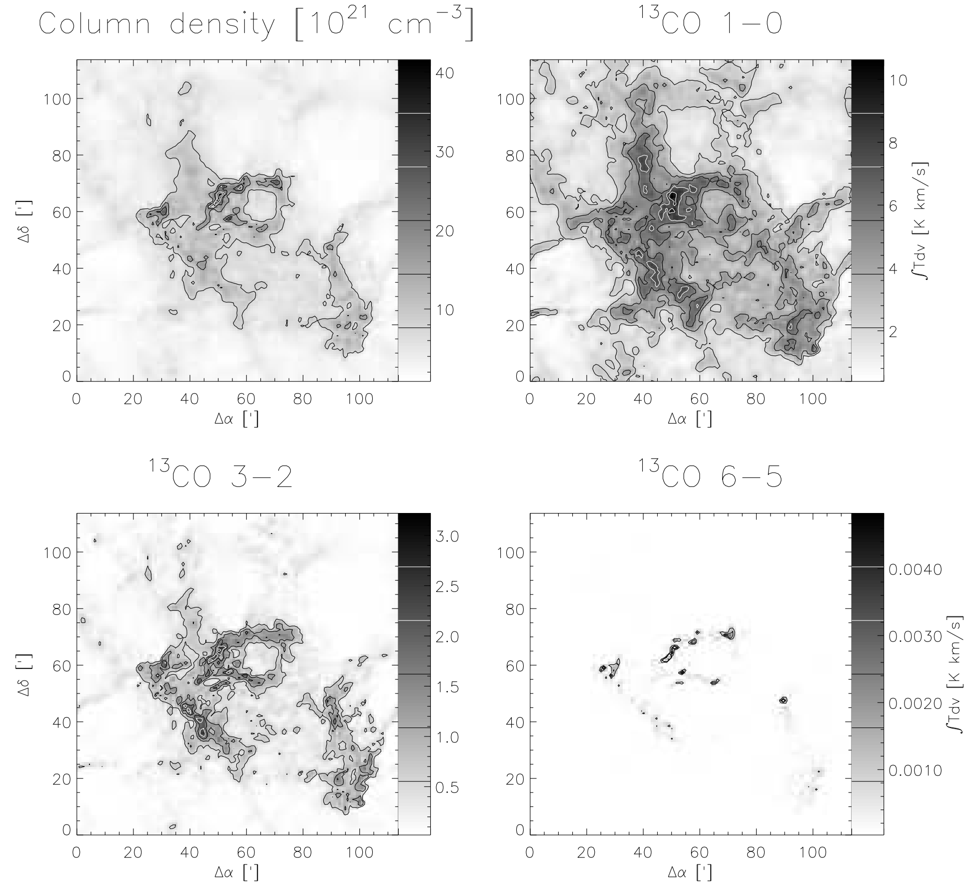


Figure 1. Column density and integrated line maps in three $^{13}$CO transitions for a hydrodynamic turbulence model driven on large scales.

as created e.g. by shock fronts, shells and outflows. Adapted anisotropic filters (see e.g. Forbes & Thomson 1992) seem to be a promising way here. Anisotropy measures like the ratio between the squared maximum diameter and the area of iso-intensity contours (Adams & Wiseman 1994) also need further investigation.

A huge amount of information on the velocity structure can be extracted from the line profiles. Ossenkopf & Mac Low (2002) have tested several methods and found that a number of independent measures has to be combined to provide a distinctive characterisation of the velocity structure. Among them are methods typically used to characterise the simulations, as probability distribution functions (PDFs), and classical methods to characterise observational data, as the size-linewidth relation for clouds and clumps (cf. Goodman et al. 1998). Ossenkopf & Mac Low (2002) have extended the latter method to a scanning-beam size-linewidth relation which is also applicable to continuous structures where the identification of separate clumps is difficult. Furthermore is provides an independent measure for the depth of a cloud along the line-of-sight. Tauber

(1996) used the velocity information given by the smoothness of line profiles to measure the size and number of coherent units contributing to the line profiles.

Another class of methods to characterise the molecular cloud structure is based on the direct identification of such units. Clump decomposition algorithms were introduced by Stutzki & Güsten (1990), Williams, de Geus, & Blitz (1994), and Ostriker, Stone, & Gammie (2001). Tests whether the clumps found by these algorithms in simulated molecular line maps reflect the properties of the clumps in the density structure of the underlying turbulence simulation showed that only the few brightest clumps, which can be identified also by eye, correspond to true density enhancements. Nevertheless, the total clump mass spectrum is a quantity which can well discriminate between different turbulent structures but it is determined by a complex interaction of the three-dimensional shape of the clumps, radiative transfer effects, and observational noise.

## 4. Results

Systematic comparisons between observational data and numerical simulations were performed by Mac Low & Ossenkopf (2000), Ossenkopf, Klessen, & Heitsch (2001), Ossenkopf & Mac Low (2002), and Ossenkopf (2002). They used isothermal turbulence models from Mac Low (1999), Klessen, Heitsch, & Mac Low (2000), and Heitsch, Mac Low, & Klessen (2001) and fractal cloud models.

Only models with a main energy injection at large scales, without strong magnetic fields and without a long dissipation history reproduce the scaling relations of the observed intensity and velocity structure. The velocity scaling behaviour of all observations and turbulence models is consistent with the interpretation of a molecular cloud as shock-dominated medium. Deviations from the self-similar behaviour point towards dissipative processes on scales below 0.05 pc which may be caused by ambipolar diffusion. However, all large-scale driven turbulence models showed typical line profiles which break up into several fragments in contrast to the profiles observed in quiescent molecular clouds. None of the turbulence models explains all of the observed structure parameters, so that a new series of cloud simulations is needed. Fractal models can be adjusted to provide a better fit to the observations due to the larger number of free parameters but they do not help to understand the physical nature of turbulent cloud fragmentation.

## 5. Summary and outlook

The systematic study of the radiative transfer in turbulent clouds has shown that each molecular transition reflects only a narrow density range. The combination of several tracers is required to obtain reliable information on the density and velocity structure. The lower transitions of all CO isotopes trace only gas at low and intermediate densities which is distributed over large scales in molecular clouds. The process of protostellar collapse cannot be observed directly in molecular lines but it can be inferred when comparing observations in different transitions taken with an excellent signal-to-noise ratio and from dedicated high-density tracers.

As long as we have no clear physical interpretation for the different measurable structure parameters many of them have to be combined to compare cloud simulations and observations. In this way one can discriminate between different models clearly excluding some scenarios and constraining the possible parameter ranges. Nevertheless, none of the studied isothermal turbulence simulations explained all observed features of the molecular cloud structure. New models should include a phenomenological description of the turbulence on scales below the resolution limit, a self-consistent treatment of the energy balance and of the cloud boundaries.

With the results presented here it is now possible to set up an iterative process of constructing new models, computing their appearance in molecular lines, and comparing them statistically to observations. By fitting more and more observational parameters the physical processes structuring molecular clouds can be identified so that we start to understand turbulent fragmentation leading to the collapse of protostars. This will finally help to answer today's questions about the initial stellar mass function, the clustering of star formation or the statistics of multiple systems.

## References

Bate, M.R. 1998, ApJ 508, L95

Forbes D.A., Thomson R.C., 1992, MNRAS 254, 723

Goodman A.A., Barranco J.A., Wilner D. J., Heyer M. H. 1998, ApJ 504, 223

Heitsch F., Mac Low M.-M., Klessen R.S. 2001, ApJ 547, 280

Juvela M. 1997, A&A 322, 943

Klessen R.S., Heitsch F., Mac Low M.-M. 2000, ApJ 535, 887

Mac Low M.-M. 1999, ApJ 524, 169

Mac Low M.-M., Ossenkopf V. 2000, A&A 353, 339

Mac-Low M.-M., Klessen R.S., Burkert A., Smith M.D. 1998, Phys.Rev.Lett 80, 2754

Ossenkopf V. 2002, A&A accepted

Ossenkopf V., Mac Low M.-M. 2002, A&A in press

Ossenkopf V., Bensch F., Stutzki J. 2000, in: The Chaotic Universe, eds. Gurzadyan V.G., Ruffini R., World Sci., 394

Ossenkopf V., Klessen R., Heitsch F. 2001, A&A 379, p. 1005

Ostriker E.C., Stone J.M., Gammie C.F. 2001, ApJ 546, 980

Padoan P., Juvela M., Bally J., Nordlund A. 1998, ApJ 504, 300

Stutzki J., Güsten R. 1990, ApJ 356, 513

Tauber J. A. 1996, A&A 315, 591

Williams J.P., de Geus E.J., Blitz L. 1994, ApJ 428, 693

Williams J.P., Blitz L., McKee C.F. 1999, in: Protostars and Planets IV, eds. Mannings V., Boss A., Russell S., Univ. Arizona Press, 98