Turbulence and Feedback from High Mass Stars

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Abstract:

We present the first characterization of the gas dynamics in a molecular cloud at scales of individual star formation. We cover scales from 70AU to 30000AU.

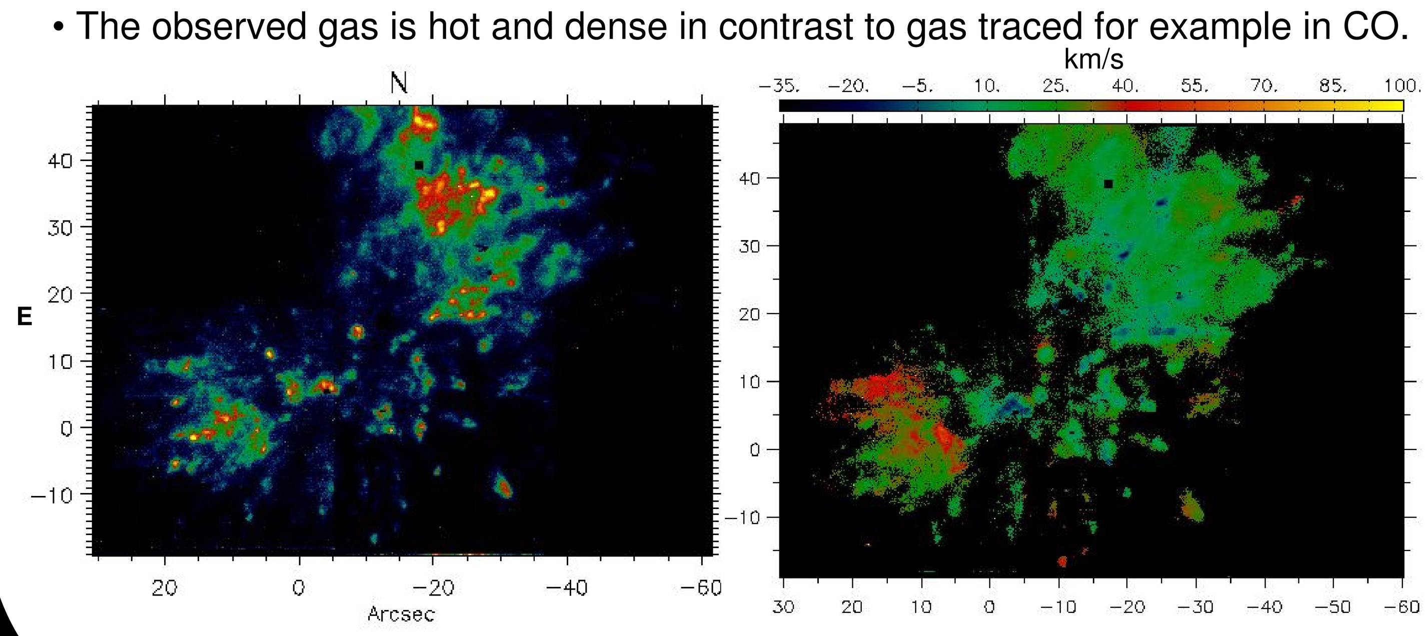
We study the velocity distribution of the gas in the massive star forming region OMC1, and show that in a statistical sense the distribution resembles a turbulent energy cascade. There is however deviations that might reflect the impact of protostellar outflows. Observational results are compared with simulations.

Introduction:

- There is good observational and numerical evidence that turbulence dominates the velocity structure of molecular clouds and cloud cores at large scales.
- Feedback (winds, outflows, jets) from young stars and especially massive stars injects energy into the cloud and have a profound effect on the gas distribution on smaller scales in the vicinity of the star.
- Feedback may redistribute the ambient gas and may cause further condensations to collapse or it may disperse the ambient gas.
- Detailed analysis of a broad range of observations are necessary on order to understand the dominating processes in the above scenario. Further insight can be gained by comparing the observational results and simulations. In many cases the interpretation depends on the simulations ability to reproduce the observational data.

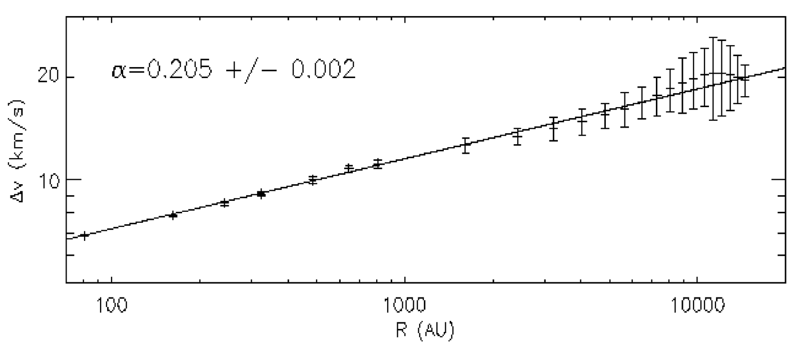
Observations:

- The Orion Molecular Cloud, OMC1, is observed at IR wavelengths using CFHT/GriF which combines adaptive optics and Fabry-Perot interferometry.
- The H_2 v=1-0 S(1) emission line at 2.12μm is scanned using the Fabry-Perot. A spectral profile of the line is obtained in every position on the sky.
- Using adaptive optics we obtain a spatial resolution of 0.15'' or 70 AU.
- The radial velocity associated with a specific position on the sky is found as the peak position in a fit to the spectral profile. Uncertainties in the velocities range from +/- 1km/s to +/- 9 km/s.
- The observed gas is hot and dense in contrast to gas traced for example in CO.



OMC: Brightness of H_2 v=1-0 S(1)   OMC1: radial velocity in km/s

Size-line width relation:



Larson (1981) [1] identified an empirical relation between linewidth (velocity dispersion) and size for molecular clouds and clumps:

$\Delta v_{obs} \sim R^{\alpha}$

Recent studies find α = 0.2-0.7 over scales of 0.02-100pc.

We have calculated the average velocity dispersion of the radial velocities in our map within circular regions of varying size and find a good power law agreement (see figure). The scaling exponent is α=0.205 ± 0.002. This agrees with the average value of 0.21 ± 0.03 that [2] found in Orion A and B at scales 0.03 - 1pc using CO as an indicator.

Our data extend the validity of the Larson relationship to smaller scales by ~2 orders of magnitude with a similar exponent as for massive cores.

Structure functions:

Structure functions are very useful for comparison between observations, numerical simulations and theory. They measure the spatial correlations in the velocity field. The structure functions of order p are defined as:

$$S_p(L) = \langle |\, v(\boldsymbol{r}) - v(\boldsymbol{r}-\boldsymbol{\tau})\,|^p \rangle = \langle |\, \Delta v \,|^p \rangle$$

v is the radial velocity, $\boldsymbol{r}$ is a spatial position and $\boldsymbol{\tau}$ is a 2D spatial vector. The averaging is performed over all pixel pairs where L= |τ|.

In a homogenous, isotropic, turbulent medium it is expected that

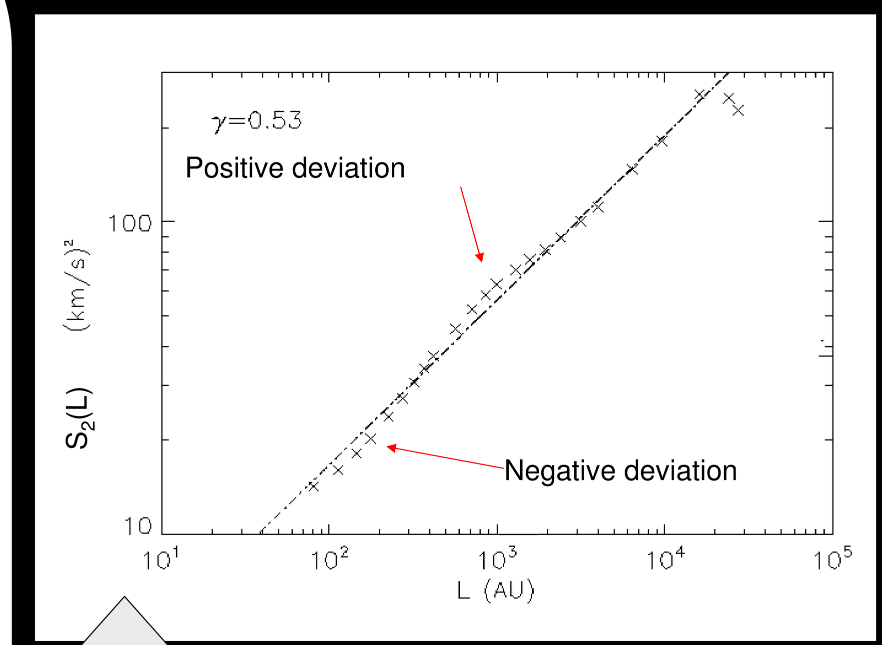
$$S_p(L) \propto L^{\gamma(p)}$$

The second order structure function (p=2), see figure to the right, resembles a power law at large scales (>3000 AU) as found in turbulent regions.

The best power law fit to the data (dash-dotted line in figure) yields an exponent $\gamma(2)=0.53$, which agrees with values found in other molecular clouds at larger scales.

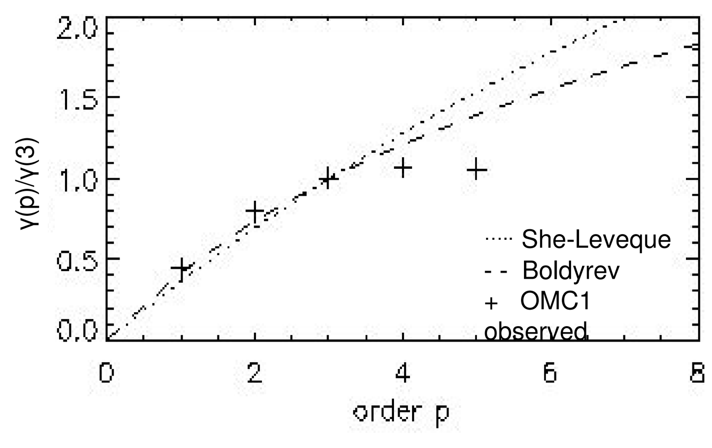
The velocity structure in OMC1 is however not well represented by a single power law (see figure). The 2nd order structure function deviates significantly from a power law at scales below 2000AU.

The physical meaning of $S_2(L)$ is that it represents all energy in eddies below the scale L. The positive deviation around 500 - 2000 AU and the negative deviation around 100 – 300 AU may reflect a redistribution of energy inflicted by the protostellar outflow(s) present in the region.



Scaling relations:

The scaling of the power law exponents, $\gamma(p)/\gamma(3)$, can be compared with theoretical scaling relations.



The She-Leveque scaling for incompressible, subsonic turbulence [3]:
$\gamma(p) / \gamma(3) = p/9 + 2(1-(2/3)^{p/3})$

The Boldyrev scaling for supersonic turbulence [4]:
$\gamma(p) / \gamma(3) = p/9 + 1-(1/3)^{p/3}$

The scaling found in OMC1 deviates from the theoretical scalings

Simulations:

3D hydrodynamic simulations of turbulence are used to compare with the observational results. The simulations are done using the PENCIL-CODE and does not include self-gravity or magnetic fields. Mach number = 3.

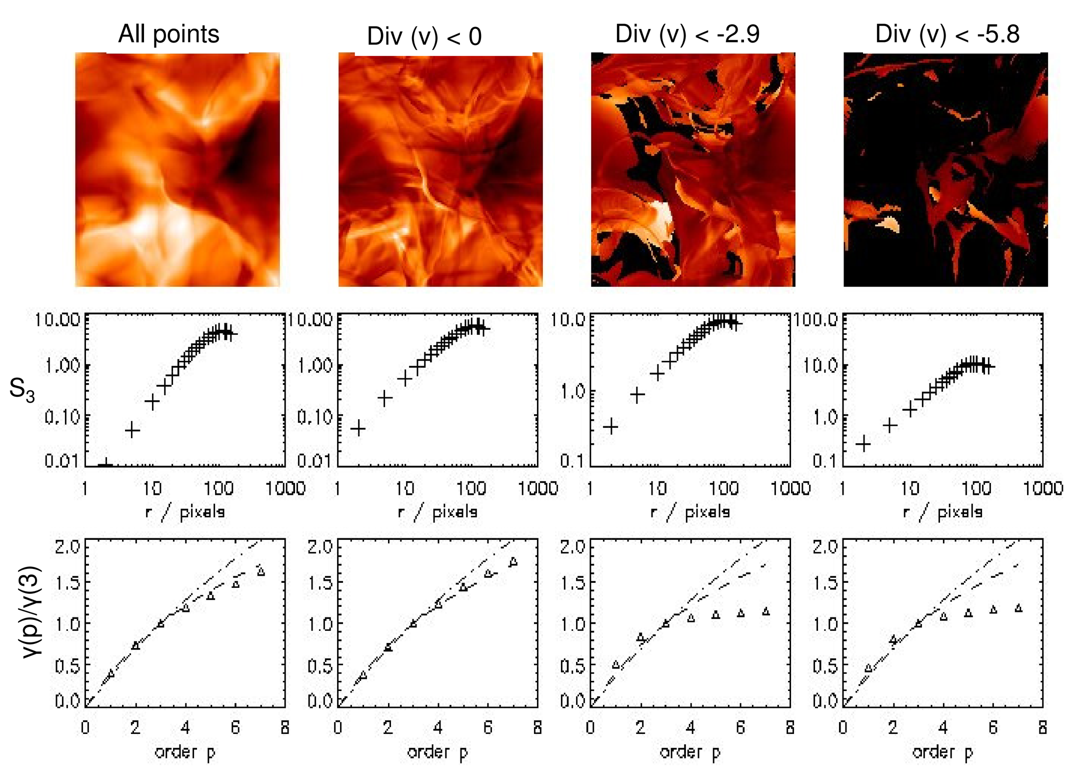
In order to compare with the observations of shocked H_2 we extract regions in the simulations were shocks occur. These regions are identified as regions with a large negative divergence value, Div(v) <0.

We make restrictions on the strength of the shock, that is, only include points with divergence values more negative than a certain threshold and collapse the 3D cube into a 2D map of radial velocities. From these maps we calculate the structure functions.

The figure shows 4 collapsed subsets of the simulation and the associated 3rd order structure function and scaling of exponents. For subsets including all points and all points with Div(v) <0 the scaling follow that of Boldyrev [4]. When weak shocks are excluded, Div(v) < -2.9 the scaling is similar to that observed in OMC1.

The structure functions are in all events good power laws and no deviations are seen.

The unusual scaling relation in OMC1 can be explained by the fact that we observe preferentially shocked gas. The preferred scales in the structure functions remain to be reproduced in simulations.



(Δ): simulations, (···) She-Leveque, (- -) Boldyrev

MORE INFO:

Gustafsson et al (2006), A&A 445, 601

Gustafsson et al (2006), A&A 454, 815

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Conclusions and Outlook:

Our IR observations have allowed us to characterize the velocity field in a star forming region at scales two orders of magnitude lower than what has previously been possible using radio data to trace CO.

Some trends observed at larger scales are reproduced here: the size-linewidth relation. Some are not: structure functions deviate from power laws.

The latter could be an effect of protostellar outflows, but this needs to be confirmed by simulations and other observations.

As follow-up to this initial study we plan to include outflows from high mass stars in the simulations in order to reproduce the power law deviations found in OMC1.

It should also be tested whether the velocity field in other star forming regions show the same characteristics as OMC1 with respect to the sizes of preferred scales (if any) and the scaling of structure functions.

References:

[1] Larson, 1981, MNRAS, 194, 809, [2] Caselli & Myers 1995, ApJ, 446,665, [3] She& Leveque 1994, Phys. Rev. Lett. 72, 336, [4] Boldyrev 2002, ApJ, 569, 841