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Fragmentation and dynamics in Massive Dense Cores in Cygnus-X

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Abstract. A systematic, high angular-resolution study of IR-quiet Massive Dense Cores (MDCs) of Cygnus-X in continuum and high-density molecular tracers is presented. The results are compared with the quasi-static and the dynamical evolutionary scenario. We find that the fragmentation properties are not compatible with the quasi-static, monolithic collapse scenario, nor are they entirely compatible with the formation of a cluster of mostly low-mass stars. The kinematics of MDCs shows individual velocity components appearing as coherent flows, which indicate important dynamical processes at the scale of the mass reservoir around high-mass protostars.

Keywords. stars: formation, ISM: kinematics and dynamics

1. Introduction

Two competing scenario is challenged by observations to describe the formation of high-mass stars, a quasi-static model (known also as core accretion model) versus a highly dynamical model, also known as competitive accretion. The former one is a turbulence regulated scenario, where a high level of micro-turbulence balances gravity complementing the thermal pressure (e.g. McKee & Tan, 2002). This scenario describes the formation of high-mass stars as a scaled-up version of the low-mass, quasi-static star-formation process. Accretion rates of up to $\sim 10^{-3}$ $M_{\odot}yr^{-1}$ are reached for these turbulent, massive cores, which is high enough to overcome radiation pressure and enables the protostar to collect a mass larger than 8-10 $M_{\odot}$. Alternatively, dense cores may form and evolve via highly dynamical processes (e.g Vázquez-Semadeni *et al.* 2002; Heitsch *et al.* 2008; Klessen & Hennebelle, 2009), where large-scale turbulent flows create structures by shock-dissipation and, as shown by numerical simulations, supersonic turbulence fragments the gas efficiently in very short time-scales (Padoan *et al.* 2001; Vazquez-Semadeni *et al.* 2007). Gravitationally bound density fluctuations created in this picture of *gravo-turbulent fragmentation* are the seeds for star-formation. Bonnell *et al.* (2001) proposed that in a clustered environment some of these seeds may continue to accrete material from regions which were originally not bound to their protostellar envelope and therefore compete for mass in the central parts of clusters forming high-mass stars. This scenario is introduced as *competitive accretion* (see also Bonnell & Bate, 2006).

We present here a systematic, high angular-resolution study towards five IR-quiet Massive Dense Cores (MDCs) in Cygnus-X. These MDCs lack mid-IR emission (>8μm), but host powerful outflows, therefore must be in an early evolutionary stage. They have masses between 60-200 $M_{\odot}$ with 10× higher volume densities than nearby cores and therefore serve as the best prototypes to observationally constrain the turbulence regulated, quasi-static or a highly dynamical formation scenario. Cygnus X is located at 1.7 kpc and using high angular-resolution IRAM PdBI continuum and molecular line

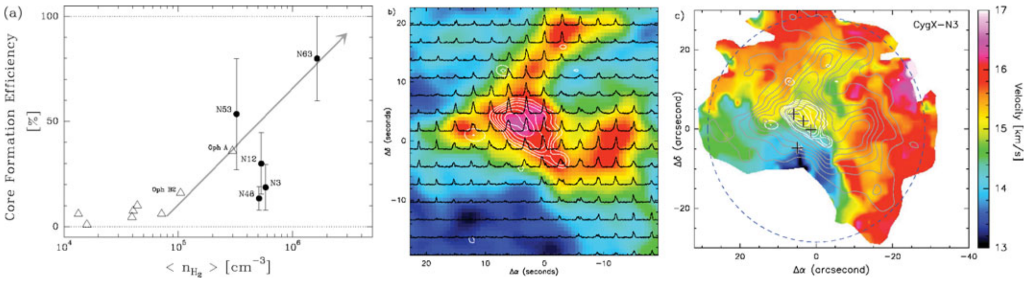

Figure 1. *a)* Core/condensation formation efficiency as a function of the average densities for dense cores of similar sizes (FWHM$\sim$0.1 pc) but of different masses in Cygnus MDCs (filled symbols) and in ρ Ophiuchus (open triangles; Motte *et al.* (1998)). A transition from low efficiency cores to possible, single collapsing cores is observed from a few 10^4 to a few 10^6 cm^{-3}. *b)* CygX-N3 is shown as an example of the sample of 5 MDCs, the $H^{13}CO^+$ (J=1–0) integrated intensity maps and spectra map with the 3mm continuum contours in white overlaid, *c)* a map of the position of the spectra peak, which represents the velocity field of the bulk material, crosses mark the position of the four 1mm continuum sources, white contours shows the 3mm continuum emission and grey contours represent the integrated emission of $H^{13}CO^+$.

observations at 1mm and 3mm offers the opportunity of reaching small scales (less than 2000 AU at 1mm and 6000 AU at 3mm) to identify individual collapsing objects. The analysis of the continuum maps allowed us to separate individual protostars (Sect.2.), and the line emission is the perfect probe of the kinematics of the gas in the MDCs (Sect.3.).

2. Fragmentation

These MDCs in Cygnus X are expected to collapse either to form a single (or binary) high-mass star or they might be sub-fragmented into a cluster of mostly low-mass protostars. Bontemps *et al.* (2010) studied the fragmentation properties of these MDCs and found that they are actually sub-fragmented but not in a too large number of fragments. Only the most compact core, CygX-N63, is not sub-fragmented and seems to correspond to a single massive protostar with an envelope mass of 60$M_\odot$. The fragments inside the other cores have sizes and separations similar to low-mass proto-stellar objects in nearby proto-clusters. A total of 23 fragments are resolved in the sample with typical sizes of $\sim$4000 AU and masses between 2 and 55$M_\odot$. Nine of them are found to be massive enough to be precursors of OB stars. We conclude that the level of fragmentation in 4 out of 5 MDCs is higher than in the turbulence regulated collapse scenario, but is not as high as expected in a pure gravo-turbulent scenario where the distribution of mass is dominated by low-mass protostars. In addition we find that the densest MDCs have a large fraction of their total mass in only a few massive fragments (Figure 1 *a*) showing that they have an exceptionally high core formation efficiency with a clear excess of massive fragments in their central regions which are then proposed to correspond to the expected primordial mass segregation of stellar clusters.

3. Kinematics

To go one step further in understanding the origin of these massive fragments, Csengeri *et al.* (2010) studied the high-density tracers $H^{13}CO^+$ and $H^{13}CN$ at high angular-resolution obtained with the PdBI. We consider that such high-density tracers represent well the common mass reservoir of the high-mass protostars (see the structures in Figure 1 *b*). Thus, there is either a high level of micro-turbulence, which provides sufficient support against gravity and keeps the MDCs in a quasi-static evolution

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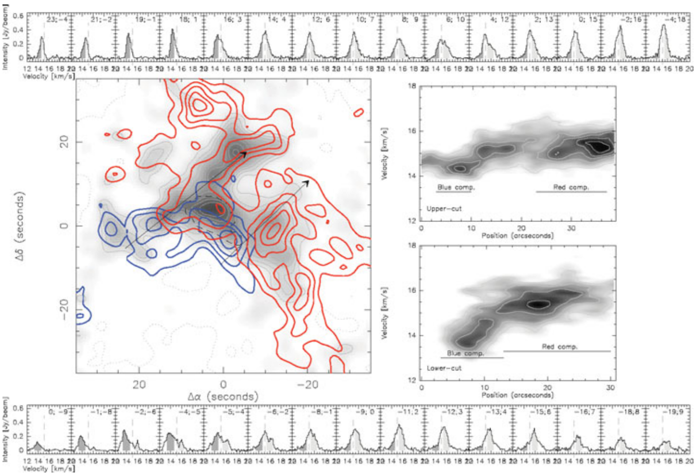

Figure 2. Map of CygX-N3 in $H^{13}CO^+$ obtained with the PdBI and zero-spacings added. The grey scale shows integrated intensity between 14.5-15.5 km s^{-1}. Blue contours correspond to integrated intensity between 13.5-14.5 km s^{-1} and red contours show integrated intensity between 15.5-16.5 km s^{-1}. Contours go from 5×rms noise and are increased by steps of 3×rms noise. Black contour shows the 30% of the peak intensity of the 3mm continuum maps. Fully sampled spectra are extracted in two cuts following two filamentary structures, where the position corresponding to each spectra are shown in the upper right corner. The integration ranges from the blue shifted component are in dark grey and white grey shows the red component. The local rest velocity of the MDC is shown by dashed grey line. The right panels show cuts of spectra represented in position-velocity diagrams for both cuts, respectively.

towards a monolithic collapse. Alternatively, the MDCs may not be in equilibrium and their formation and evolution is mostly driven by dynamical processes. The spectra overlays in Figure 1 *b)* show that all MDCs exhibit complex kinematics in $H^{13}CO^+$ with several individual velocity components, which are separated and dispersed over ∼1 to 3 km s^{-1}.

The velocity field of all MDCs is determined by extracting the velocity of the peak intensity of the spectra. We find that three MDCs show dominant organized velocity fields, while in the others no global gradient is seen. Figure 1 *c)* shows the example with a velocity gradient perpendicular to the axis of the continuum fragments. The velocity gradients cover a range of 1.2 - 4.1 km s^{-1} pc^{-1} for the total sample. We calculated the ratio of rotational versus gravitational energy, and we find that even if systematic motions were due to rotation only, the rotational energy would negligible compared to the gravitational (E_{rot}/E_{grav}<0.025). Recent numerical simulations by Dib *et al.* (2010) report a variety of dynamical patterns for cores formed in a turbulent, magnetized and self-gravitating molecular clouds ranging from easily recognizable rotational features to more complex ones.

At high angular resolution the individual spectral components may correspond to coherent structures within the mass reservoir around the high-mass protostars. We studied the distribution of gas by disentangling the individual spectral components as shown for example in Figure 2. Coherent velocity features were extracted by integrating around the local rest velocity and in the blue and red-shifted velocity range, which components are shown as contours. We find sub-filaments, which are perpendicular to the main filament containing the 3 most massive fragments seen in continuum emission. The velocity pattern of these sub-filaments shows velocity drifts and shears within them implying a high level of dynamics with organized motions at these small scales.

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4. Discussion & Conclusions

The high angular-resolution observations reveal rich and complex kinematics of dense gas around massive protostars in our sample of MDCs. Since the high mass protostars reside in the center of MDCs and the gravitational well is the deepest there, we interpret the above demonstrated coherent velocity features with filamentary structure (Figure 2) as flows converging to the central part of MDCs. We suggest that the interaction point of these flows is coincident with the continuum peaks, e.g. the high-mass protostars. The relative velocity difference of these small-scale flows and velocity shears may indicate $\sim 10^4$ yr dynamical time-scales for new protostellar seeds to built up. These estimated crossing times are comparable to the free-fall time-scales of the individual protostellar fragments suggesting that such flows may play an important role in building up the final mass of high-mass protostars. This is compatible with numerical simulations with high dynamics and competitive accretion.

The dynamical processes seem to govern also the formation of MDCs as it was recently shown by Schneider *et al.* (2010) for the DR21 filament, a 10 pc-scale very high density massive structure in Cygnus-X. To summarize, Bontemps *et al.* (2010) and Csengeri *et al.* (2010) present a systematic, high angular-resolution study of 5 MDCs in Cygnus-X focusing on their fragmentation properties and the kinematics of the mass reservoir, from which high-mass protostars form. The main findings are:

(*a*) The MDCs of Cygnus-X are found to be sub-fragmented with a total of 23 fragments within 5 MDCs. They have masses up to 55 $M_\odot$ and 9 of them may potentially form high-mass protostars.

(*b*) High angular-resolution maps of high density tracers as $H^{13}CO^+$ reveal a significant substructure of the mass reservoir around the high-mass protostars. In all MDCs several velocity components are found, which are disentangled into small-scale coherent flows with intrinsic velocity gradients and/or velocity shears.

(*c*) The relative difference in velocity position of the flows give dynamical time-scales of the order of the free-fall time-scale for 4 out of 5 MDCs.

(*d*) Therefore we suggest that the evolution of MDCs is driven more by dynamical processes than quasi-static evolution in a turbulent medium.

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