CONVERGENT FLOWS AND LOW-VELOCITY SHOCKS IN DR21(OH)

T. Csengeri1,2, S. Bontemps3, N. Schneider2, F. Motte2, F. Gueth4, and J. L.Hora5

1 Max Planck Institute for Radioastronomy, Auf dem Hügel 69, 53121 Bonn, Germany; ctimea@mpifr-bonn.mpg.de
2 Laboratoire AIM Paris Saclay, CEA-INSU/CNRS-Université Paris Diderot, IRFU/SAp CEA-Saclay, 91191 Gif-sur-Yvette, France
3 OASU/LAB-UMR5804, CNRS, Université Bordeaux 1, 33270 Floirac, France
4 IRAM, 38406, Saint Martin d’Hères, France
5 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS-65, Cambridge, MA 02138, USA

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ABSTRACT

DR21(OH) is a pc-scale massive, $\sim$7000 $M_\odot$ clump hosting three massive dense cores (MDCs) at an early stage of their evolution. We present a high angular resolution mosaic, covering $\sim$70$''$ \times 100$''$, with the IRAM Plateau de Bure Interferometer at 3 mm to trace the dust continuum emission and the N$_2$H$^+$ ($J = 1-0$) and CH$_3$CN ($J = 5-4$) molecular emission. The cold, dense gas traced by the compact emission in N$_2$H$^+$ is associated with the three MDCs and shows several velocity components toward each MDC. These velocity components reveal local shears in the velocity fields which are best interpreted as convergent flows. Moreover, we report the detection of weak extended emission from CH$_3$CN at the position of the N$_2$H$^+$ velocity shears. We propose that this extended CH$_3$CN emission is tracing warm gas associated with the low-velocity shocks expected at the location of convergence of the flows where velocity shears are observed. This is the first detection of low-velocity shocks associated with small (subparsec) scale convergent flows which are proposed to be at the origin of the densest structures and of the formation of (high-mass) stars. In addition, we propose that MDCs may be active sites of star formation for more than a crossing time as they continuously receive material from larger scale flows as suggested by the global picture of dynamical, gravity-driven evolution of massive clumps which is favored by the present observations.

Key words: ISM: kinematics and dynamics – stars: formation

Online-only material: color figures

1. INTRODUCTION

Two competing scenarios are challenged by observations to describe the formation of rich clusters and of high-mass stars: a quasi-static evolution (also known as core accretion model) versus a highly dynamical model. The first one is a turbulence-regulated scenario, where a high level of micro-turbulence acts as an effective additional thermal pressure to balance gravity (e.g., McKee & Tan 2002). In the second one, massive cores form and evolve via highly dynamical processes (e.g., Bonnell & Bate 2006; Vázquez-Semadeni et al. 2007; Heitsch et al. 2008; Hennebelle et al. 2008; Klessen & Hennebelle 2010), where convergent flows driven by large-scale turbulence, gravity, and Galactic motions create dense structures down to small scales by shock dissipation at their stagnation points (e.g., Field et al. 2008; Vázquez-Semadeni et al. 2011).

In the Cygnus X region, a population of massive dense cores (hereafter MDCs) was revealed by a systematic dust continuum survey (Motte et al. 2007). The most massive of them are the birthplace of high-mass stars (Bontemps et al. 2010). Among the MDCs more massive than 40 $M_\odot$ all show star formation activity, leading to the suggestion that the formation of high-mass stars within MDCs is a fast process (Motte et al. 2007). Csengeri et al. (2011) indeed recognized the important role of dynamical processes inside the young IR-quiet MDCs with crossing times only slightly larger than the local free-fall times, confirming a fast evolution. The precise origin of the MDCs and of their prime properties (mass, size, spatial distribution) is still uncertain as well as one needs to understand how a rich cluster can be formed from relatively small MDCs (see discussion in Bontemps et al. 2010). Csengeri et al. (2011) also proposed that the massive protostars in the MDCs are found at the location of velocity shears by the convergence of small-scale flows. The existence of these convergent flows however needs confirmation by, for instance, the direct detection of the associated low-velocity shocks (e.g., Klessen et al. 2005).

The clump associated with DR21(OH) is the most massive 1 pc scale clump of the whole Cygnus X region. It is embedded in the DR21 filament which contains as much as 30% of the total mass in dense gas imaged by Motte et al. (2007; see also Schneider et al. 2010), and contains three 0.1 pc scale MDCs: CygX-N44, CygX-N48, and CygX-N38. CygX-N44 hosts several spots of OH, H$_2$O maser emission (Plambeck & Menten 1990; Liechti & Walmsley 1997) and at high angular resolution two strong peaks of continuum emission were identified (Woody et al. 1989; Mangum et al. 1991; MM1 and MM2 in Figure 1). The brightest peak, MM1, contains a “hot core” ($T \sim$ 100 K) and shows centimeter continuum emission (Mangum et al. 1991) suggesting the recent birth of high-mass star(s). CygX-N48 and CygX-N38 have no mid-IR emission and host cold gas ($T < 40$ K; Mangum et al. 1992).

With such a high mass, the DR21(OH) clump qualifies as the best target in nearby regions (at less than 3 kpc) to probe the initial conditions of a rich and massive protocluster. It is expected to form a cluster as rich or even richer than the Orion Nebula Cluster.7 We mapped DR21(OH) at high angular resolution at 3 mm continuum, and in the N$_2$H$^+$ ($J = 1-0$), and CH$_3$CN ($J = 5-4$) molecular lines with the Plateau de Bure Interferometer (PdBI) to trace the cold, dense gas and warm gas with complex chemistry, respectively.

6 We adopt a distance of 1.7 kpc (Schneider et al. 2006).
7 Assuming a star formation efficiency of 30%, the $\sim$7000 $M_\odot$ of DR21(OH) would produce a stellar mass of 2100 $M_\odot$, which is more than twice the stellar masses in the Orion Nebula Cluster (Hillenbrand 1997).
2. OBSERVATION AND DATA REDUCTION

A mosaic with three pointings was obtained with the IRAM\(^8\) PdBI with six antennas in Bq and Cq configurations between 2008 December and 2009 March. Baselines range from 24 to 452 m and \(T_{\text{sys}}\) was \(\sim 100–150\) and \(60–80\) K for the B and C tracks, respectively. The signal was correlated at 93.17613 and 91.98705 GHz in order to obtain the \(^{12}\)N\(_2\)H\(^+\) (\(J = 1–0\)) and CH\(_3\)CN (\(J = 5–4\), \(K = 0–4\)) lines, respectively, with a velocity resolution of \(\sim 0.25\) km s\(^{-1}\). Line-free continuum emission was obtained with six broadband correlator units. We used as phase calibrator the bright nearby quasar 2013+370 and as flux calibrator the bright evolved star MWC 349.

We used the GILDAS software\(^9\) for the data reduction and analysis and applied the same method for all data sets. Zero-spacing information was available only for the \(^{12}\)N\(_2\)H\(^+\) (\(J = 1–0\)) and CH\(_3\)CN (\(J = 5–4\), \(K = 0–4\)) lines, respectively, with a velocity resolution of \(\sim 0.25\) km s\(^{-1}\). Line-free continuum emission was obtained with six broadband correlator units. We used as phase calibrator the bright nearby quasar 2013+370 and as flux calibrator the bright evolved star MWC 349.

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3. \(^{12}\)N\(_2\)H\(^+\) AS A TRACER OF THE COLD, YOUNG GAS

\(^{12}\)N\(_2\)H\(^+\) is a tracer of cold, dense gas (Tafalla et al.\(^2\) 2002). Since it is quickly destroyed in the heated envelopes of protostars, it shall represent the starless/unprocessed gas, which has either

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\(^9\) See http://www.iram.fr/IRAMFR/GILDAS/.

\(^10\) We exploit here both the combined and the interferometric-only data set of the \(^{12}\)N\(_2\)H\(^+\) data, because the latter one filters out extended emission from the clump and shows the compact emission, which is the main focus of this Letter.

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Table 1

| Parameters of the Observations | PdBI | Synthesized Beam (\(\prime \times \prime\)) | P.A. | rms (mJy beam\(^{-1}\)) |
|-------------------------------|------|----------------------------------|------|----------------------|
| 3 mm continuum                | 2.11 \(\times\) 1.9 | 84\(^\circ\) | 0.3 |
| \(^{12}\)N\(_2\)H\(^+\) (\(J = 1–0\)) | 2.09 \(\times\) 1.89 | 84\(^\circ\) | 8.9 |
| CH\(_3\)CN (\(J = 5–4\), \(K = 0–4\)) | 2.13 \(\times\) 1.92 | 83\(^\circ\) | 9.1 |

Note. For the molecular lines the rms noise is given for 0.25 km s\(^{-1}\) spectral resolution.

not yet fragmented or originates from recently formed pre/protostellar cores.

In a quasi-static view of star formation, the pre-collapse core traced by \(^{12}\)N\(_2\)H\(^+\) is expected to evolve to a higher level of concentration by a progressive loss of support until it gets gravitationally unstable and collapses. In nearby low-mass star-forming regions such as \(\rho\) Ophiuchi, \(^{12}\)N\(_2\)H\(^+\) is indeed found to show single, narrow lines which are consistent with being close to or under gravitational collapse with only a small contribution from nonthermal motions (André et al.\(^11\) 2007).

3.1. Compact \(^{12}\)N\(_2\)H\(^+\) Emission is Concentrated in the MDCs

In Figure 1(a), the spatial distribution of \(^{12}\)N\(_2\)H\(^+\) at low (IRAM 30 m) and high (PdBI) spatial resolution is compared with the dust continuum emission which is taken as a reference to trace the total column density.

Seen with a single-dish telescope the distribution of \(^{12}\)N\(_2\)H\(^+\) differs from the dust continuum (Figure 1(a)), as \(^{12}\)N\(_2\)H\(^+\) peaks in the south of the clump between CygX-N48 and CygX-N38. This prominent north–south inhomogeneity indicates that generally the southern part of the clump is younger than the northern part. At high spatial resolution with the PdBI (Figure 1(b)), the compact emission of \(^{12}\)N\(_2\)H\(^+\) is clearly concentrated in the three known MDCs: CygX-N48, CygX-N38, and CygX-N44. This discrepancy of the distribution of \(^{12}\)N\(_2\)H\(^+\) seen with the
single-dish telescope compared to the interferometer shows that a large fraction of the \( \text{N}_2\text{H}^+ \) emission originates from extended structures that are filtered out by the interferometer. It also shows that the most compact components of \( \text{N}_2\text{H}^+ \), and therefore the densest parts of this unprocessed, cold gas are associated with the MDCs in the clump.

At high angular resolution this spatial coincidence between the dust and \( \text{N}_2\text{H}^+ \) and the fact that both tracers seem to form structures at similar size scales of \( \sim0.1 \) pc further confirms the existence of a typical size scale for MDCs and indicates that the MDCs are the main sites of present star formation. In contrast, the hot-core region of DR21(OH)-MM1 is devoid of such structures at similar size scales of \( \sim \). The range of the \( v \) velocity axis is from \(-8\) to \(+0.5 \) \( \text{km s}^{-1} \). The intensity range, \( y \)-axis, scales from \(-0.1\) to \(0.4\) Jy beam\(^{-1}\). Dots mark the position of a grid sampled on half of the beam. Green crosses point the positions where spectra are extracted and shown in panels (b) and (c). (b and c) Extracted spectra toward the three positions in CygX-N48 and CygX-N38. Red and blue shading indicates the integration ranges shown in Figure 3. (A color version of this figure is available in the online journal.)

We show in Figure 3 the maps of integrated intensity of the two velocity components which are associated with the two coldest MDCs, as well as position–velocity cuts through and across the intersection regions between the two velocity components. These cuts show velocity jumps indicated by arrows which have relative velocity difference of \( 2\sim3 \) \( \text{km s}^{-1} \) and are referred below as velocity shears. We note that the intersection regions of the velocity shears are close to the strongest peaks of continuum emission, but do not coincide exactly with them. The velocity shears are found to be offset from the strong continuum sources. These \( \text{N}_2\text{H}^+ \) velocity patterns are very similar to what we have recently obtained using \( ^{13}\text{C}^1\text{CO} \) in isolated MDCs in Cygnus X (Csengeri et al. 2011). Similarly, we propose that the individual velocity components seen in \( \text{N}_2\text{H}^+ \) are also best interpreted as flows converging to the gravitational well of MDCs. These flows may carry a significant amount of angular momentum which could lead to rotational motions. For a \( 200 \text{M}_\odot \) core the Keplerian velocity at \( 0.1 \) pc is \( \sim2.9 \) \( \text{km s}^{-1} \) which is of a similar order as the gradient observed in the velocity field. On the other hand, the \( pv \)-cuts in Figure 3 show that the maximum velocities are not found at large offsets from the velocity jumps, similar to what is expected in a Keplerian rotation, but they show a more complex distribution. The observed velocity pattern of the gas here is thus not compatible with a pure rotation of the cores. Furthermore, a homogeneous sphere in rotation would also not show separated individual velocity components.

3.2. Bulk Motions in the \( \text{N}_2\text{H}^+ \) Gas Associated with the MDCs

At low angular resolution with the IRAM 30 m telescope the spectra show a single component (Schneider et al. 2010), such as in \( \rho \) Ophiuchi, but with a large velocity dispersion of \( \sim1.3 \) \( \text{km s}^{-1} \). But while in \( \rho \) Ophiuchi the line stays single at small scales (Di Francesco et al. 2004), the \( \text{N}_2\text{H}^+ \) emission seen with the interferometer clearly splits here into individual velocity components (Figure 2).

This is a striking feature and an important difference to low-mass star-forming regions. Since we could include the zero-spacing information from the IRAM 30 m telescope, we are confident that there are no strong side lobes and filtering which could modify the line profiles. Moreover, it seems that it is toward the MDCs that the individual velocity components can be recognized the best (see Figure 2(a)).
is larger than in Csengeri et al. (2011) most probably because of the larger mass and gravitational well of the DR21(OH) clump.

3.3. On the Origin of the Clump Fragmentation into MDCs

If the \( \sim 7000 \, M_{\odot} \) DR21(OH) clump would be governed only by thermal motions and gravity, it would fragment into a large population of \( \sim 0.4 \, M_{\odot} \) fragments corresponding to the local Jeans mass\(^{11} \) which should concentrate in the central regions close to the gravitational center of the clump. Instead, the distribution of dense gas traced by N2H\(^+\) mostly reveals three centers of collapse, the MDCs. It is then not clear why the large-scale, gravitationally driven flows split to predominantly form a few MDCs dispersed over the clump. On the other hand, the observed hierarchical fragmentation is very similar to what is obtained in numerical simulations (e.g., Hennebelle et al. 2011). These models indicate that fragmentation is provoked by a complex interplay between gravity, rotation, thermal/turbulent pressure, and magnetic forces (Vázquez-Semadeni et al. 2007) which may make it difficult to clearly pinpoint the physical origin of the observed fragmentation properties.

3.4. Are MDCs Living for More than a Crossing Time?

Since the gas dynamics dominate the evolution of the MDCs, the crossing times\(^{12} \) of the MDCs, ranging from 5 to 7 \( \times 10^4 \) yr, should measure the lifetime of the presently observed dense gas. On the other hand, the large-scale flows observed by Schneider et al. (2010) are massive enough to continuously replenish the mass of the MDCs keeping them “active” for a longer period if the local gravitational wells are spatially stable. The presence of still active N2H\(^+\) convergent flows at the location of each MDC favors this view of stable gravitational wells over time and thus suggests that the MDCs are refilled (by large-scale flows) over longer times.

It is also striking to see that all three MDCs are situated close to embedded IR-bright sources likely excited by embedded massive stars (see Figure 4). This reveals the presence of a population of young stars which could have been formed at an earlier time inside the same three MDCs.

4. CH3CN REVEALS EXTENDED WARM GAS IN EACH MDC

4.1. Intriguing Extended CH3CN Emission in All MDCs

A map of integrated CH3CN emission over all \( K = 0–4 \) components is shown in Figure 1(d). CH3CN has long been considered to be produced only in hot cores and hot corinos (e.g., Kurtz et al. 2000; Bottinelli et al. 2004) as a second-generation molecule formed in the gas phase after ice sublimation resulting in very compact emission toward protostars. As expected, a bright, compact peak of CH3CN emission is centered on the hot core source MM1 (Figure 1(d)). Among the other continuum sources, we do not detect any similar strong and compact CH3CN emission which would indicate hot cores.

In addition to the compact emission of MM1, widespread extended emission of CH3CN is detected toward all MDCs of the region, including the colder ones, CygX-N38 and CygX-N48. This extended emission is associated with the MDCs but is in detail almost entirely anti-correlated with the dust continuum (Figures 3(b) and (e)). In CygX-N48, it forms...
Figure 4. Color composite image of Spitzer IRAC 3.6 μm, 4.5 μm, and MIPS 24 μm (Hora et al. 2009). Contours show the 3 mm continuum emission obtained with the PdBI. Note the bright embedded sources close to the MDCs. Note also that there is a faint 24 μm emission at CygX-N38 which is an artifact of the MIPS point-spread function due to the nearby bright source.

(A color version of this figure is available in the online journal.)

an elongated structure almost perpendicular to the dust emission. In CygX-N38, it is shifted by 5″ from the dust continuum. This indicates that CH$_3$CN has to be overabundant in the gas (in comparison with the bulk of gas traced by the continuum) to explain this particular spatial distribution.

4.2. Is CH$_3$CN Tracing Shocks of the Convergent Flows?

In Figures 3(b) and (e), the two main N$_2$H$^+$ velocity components are overlaid on the CH$_3$CN emission. CH$_3$CN seems to be bright at the location of the velocity shears (interfaces between the red and blue velocity components) discussed in Section 3.2, and which we interpret as tracing N$_2$H$^+$ convergent flows. It is striking that CH$_3$CN coincides much better with these velocity shears than with the dust continuum. Therefore we suggest that CH$_3$CN could trace warm gas associated with the shocks expected at the convergence of the flows.

CH$_3$CN has actually been detected toward a young protostellar outflow shock in L1157 (Codella et al. 2009). The abundance of CH$_3$CN can have significant contribution from grain surface chemistry (Garrod et al. 2008) producing CH$_3$CN directly on ices. A higher CH$_3$CN abundance could originate in warm gas from ice sublimation. The involved velocities are however here smaller than in outflows, 2–3 km s$^{-1}$ in projection which converts to 3.7–5.5 km s$^{-1}$ if corrected for an average projection angle.\textsuperscript{13} From Figure 3 in Kaufman & Neufeld (1996) we see that the resulting post-shock gas temperature could be close to 100 K for a magnetized C-shock. At this gas temperature, the grains stay however cold and ice sublimation is not expected (Draine et al. 1983). Partial desorption has however been recently proposed to explain gas phase abundance of complex molecules (Garrod et al. 2007; Arce et al. 2008; Öberg et al. 2009). The higher gas temperature and sputtering of grain mantle in the shock may have led to an increased desorption of CH$_3$CN which could explain the detectable abundance of CH$_3$CN in the gas phase which is otherwise virtually not present in the cold, dense gas.

5. CONCLUSIONS

It is striking that N$_2$H$^+$, a classical tracer of cold, dense gas, shows flows associated with the highest density regions forming new high-mass stars. These flows are showing velocity shears which are found to spatially coincide with intriguing extended CH$_3$CN emission.

The evolution of the MDCs is driven by supersonic flows which are able to continuously supply a replenishment of material thanks to large-scale flows (see Schneider et al. 2010) while the MDCs form stars. As a consequence, they maintain active star-forming processes for longer than their free-fall times and crossing times if the convergent point of flows is stable in space over time.

The spatial coincidence between the N$_2$H$^+$ velocity shears and the intriguing extended emission in CH$_3$CN indicates that we have probably detected for the first time the effect of

\textsuperscript{13} The true post-shock velocities could be higher if the flows accelerate in the gravitational potential of the MDCs.
low-velocity, but high-density shocks expected in the case of widespread convergent flows building up new high-density gas in the MDCs.

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