The **astrochemical link** between dark clouds and hot cores?
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Sarah Fechtenbaum
Star Formation meeting
03/10/15
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CygX-N63: a lovely protostar
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Found by Motte et al. 2007
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Simple

Isolated

Young

VLA image at 8.4 GHz
CygX-N63: a lovely protostar

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Massive

~44 M⊙ in 2500 AU
350 L⊙

Duarte-Cabral 2013
CygX-N63: a lovely protostar

Found by Motte et al. 2007

Massive

~44 M☉ in 2500 AU
350 L☉

Duarte-Cabral 2013

Future star of 20-25 M☉
Unbiased spectral survey

235 hours of observation

181 GHz observed

~2600 lines at a 4 \sigma level

10 lines / GHz

rms \sim 3 \text{ mK} \quad 9 \text{ mK} \quad 19 \text{ mK}
Unbiased spectral survey

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Chemical composition

- 95% of the lines identified
- 67 molecules
- Abundances determined for 56 molecules
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What is the origin of molecular emission?
Spatial analysis: spectral profiles

Narrow lines < 2 km s\(^{-1}\)

Including N\(_2\)H\(^+\), N\(_2\)D\(^+\), DNC, DCO\(^+\), NH\(_2\)D, C\(_3\)H, C\(_4\)H…

\[ T_{\text{ex}} = 13 \text{ K} \]
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\(T_{\text{ex}} = 13\ \text{K}\)

Envelope tracers
Spatial analysis: spectral profiles

Broad lines

A large part of the molecules, including $\text{H}_2\text{CO}$, HCN, CS, CN

$T_{\text{ex}} = 14$ and $17 \text{ K}$
Spatial analysis: spectral profiles

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SiO, SO have a very broad component
Spatial analysis: spectral profiles

Broad lines

A large part of the molecules, including H$_2$CO, HCN, CS, CN

T$_{ex} = 14$ and 17 K

SiO, SO have a very broad component

Probably influenced by the outflow
Spatial analysis: population diagrams

Most of the population diagrams show a unique slope.

All oxygen-bearing COMs have two slopes: CH$_3$OH, CH$_3$CHO, CH$_3$OCH$_3$, CH$_3$OCHO, C$_2$H$_5$OH + CH$_3$CN

=> low $T_{ex}$ ~ 21 K and high $T_{ex}$ ~130 K
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\[ \Rightarrow \text{low } T_{\text{ex}} \sim 21 \text{ K and high } T_{\text{ex}} \sim 130 \text{ K} \]
Spatial analysis: PdBI observations

29 transitions observed with the PdBI
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Emission radius (AU) vs. Line width (km/s)
Spatial analysis: PdBI observations

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29 transitions observed with the PdBI
Spatial analysis - summary

- HC$_3$N
- DN
- CN
- COMs
- H$_2$CO
- D$_2$CO
- C$_4$H
- N$_2$D$^+$
- N$_2$H$^+$
- HNC
- DNC
- DC$_3$N
- HCN
- HC$_5$N
- DCN
- DCO$^+$
- HCO$^+$
Spatial analysis - summary

Extended envelope

\[ \langle \text{FWHM}_n \rangle = (2.9 \pm 0.0) \text{ km s}^{-1} \]

\[ \langle \text{FWHM}_b \rangle = (6.9 \pm 0.4) \text{ km s}^{-1} \]
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Inner envelope

\[ \langle \text{FWHM} \rangle = (2.2 \pm 0.3) \text{ km s}^{-1} \]

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Envelope + outflow / hot core

\[ \langle \text{FWHM}_n \rangle = (2.6 \pm 0.2) \text{ km s}^{-1} \]
\[ \langle \text{FWHM}_b \rangle = (8.9 \pm 0.5) \text{ km s}^{-1} \]
\[ \langle T_{\text{ex},n} \rangle = (14 \pm 2) \text{ K} \]
\[ \langle T_{\text{ex},b} \rangle = (17 \pm 2) \text{ K} \]
Spatial analysis - summary

Extended envelope

Inner envelope

Envelope + outflow / hot core

Hot core

\[ \langle \text{FWHM}_n \rangle = (2.9 \pm 0.1) \text{ km s}^{-1} \]
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\[ \langle \text{FWHM} \rangle = (3.3 \pm 0.3) \text{ km s}^{-1} \]
\[ \langle T_{ex} \rangle = (127 \pm 35) \text{ K} \]
Spatial analysis - summary

1. **Extended envelope**
   - $\langle \text{FWHM}_n \rangle = (2.9 \pm 0.0) \text{km s}^{-1}$
   - $\langle \text{FWHM}_b \rangle = (6.9 \pm 0.4) \text{km s}^{-1}$

2. **Inner envelope**
   - $\langle \text{FWHM} \rangle = (2.2 \pm 0.3) \text{km s}^{-1}$
   - $\langle T_{\text{ex}} \rangle = (13 \pm 3) \text{K}$

3. **Envelope + outflow / hot core**
   - $\langle \text{FWHM}_n \rangle = (2.6 \pm 0.2) \text{km s}^{-1}$
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   - $\langle T_{\text{ex},n} \rangle = (14 \pm 2) \text{K}$
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4. **Hot core**
   - $\langle \text{FWHM} \rangle = (3.3 \pm 0.3) \text{km s}^{-1}$
   - $\langle T_{\text{ex}} \rangle = (127 \pm 35) \text{K}$
We have found the pristine gas

**Composition**

- \( \text{N}_2\text{D}^+ \)
- DNC
- NH\(_2\text{D} \)
- DC\(_3\text{N} \)
- DCO\(^+ \)
- C\(_3\text{HD} \)
- CH\(_2\text{DCCH} \)
- HD\(_4\text{CS} \)
- c-C\(_3\text{H} \)
- C\(_4\text{H} \)

**Characteristics**

- High density \( \sim 6 \times 10^7 \) cm\(^{-3} \)
- High-level of depletion
  \[
  f_D = \frac{x(C^{17}O)_{\text{can}}}{x(C^{17}O)_{\text{obs}}} = 16
  \]
- \( T \sim 12-13 \) K
- Mean FWHM = 1.9 km s\(^{-1} \)
- Low deuteration level \( \sim 6 \times 10^{-3} \)
Comparison of the abundances

Dark clouds
Collated by Garrod et al. 2007

Hot core
Mookerjea et al. 2007

Hot corino
Cazaux et al. 2003
Wakelam et al. 2003
Jorgensen et al. 2004
Bottinelli et al. 2007
Stäuber et al. 2011

N-bearing species
Carbon chains
S-bearing

O-bearing and COMs
CygX-N63 is a **nascent hot core**

- N63 is an individual massive Class-0
- Chemical composition intermediate between a dark cloud and a hot core
- Chemically rich but not too much
- Tens of $\text{M}_\odot$ of highly depleted material
- Abundances determined for 56 species, including 13 deuterated species

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Determination of the column densities
Determination of the column densities

- Population diagrams

Population diagram of H^{13}CN
Determination of the column densities

- Population diagrams
- Detection of 37 rare isotopologues

Population diagram of $^{13}$CN
Determination of the column densities

• Population diagrams

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• LTE-model of the software CASSIS estimates the opacity

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- High density $\sim 10^6 - 10^7$ cm$^{-3}$ => probable LTE
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- Emission size estimation

Population diagram of H\(^{13}\)CN
Determination of the column densities

- Population diagrams
- Detection of 37 rare isotopologues
- LTE-model of the software CASSIS estimates the opacity
- High density $\sim 10^6 - 10^7 \text{ cm}^{-3}$ => probable LTE
- Emission size estimation
=> Reliable column densities
Determination of the abundances

Global abundances

$\sim 44 \, M_\odot$ in 2500 AU

Duarte-Cabral et al. 2013

$\Rightarrow$ global $n(H_2)$

$\Rightarrow$ Reliable global abundances
Determination of the abundances

Global abundances

~44 M☉ in 2500 AU

Duarte-Cabral et al. 2013

=> global n(H₂)

=> Reliable global abundances

Detailed abundances

• Determination of the emission size

• n(H₂) determined at different r with \( \rho \propto r^{-2} \)
The Cygnus-X region

Search for massive dense cores
PdBI observations

Bontemps et al. 2010

PdBI 3.5 mm
3.2” res. (4500 AU)
## PdBI observations

<table>
<thead>
<tr>
<th>CygX-N3</th>
<th>CygX-N12</th>
<th>PdBI 3.5 mm</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
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<tr>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td>1.1” res. (1500 AU)</td>
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Bontemps et al. 2010

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PdBI observations

CygX-N3

AB configuration
(500 AU)

PdBI 3.5 mm
3.2” res. (4500 AU)

CygX-N53

CygX-N63

PdBI 1.3 mm
1.1” res. (1500 AU)
Comparison of the abundances

![Diagram showing comparison of abundances of various molecules in different high-mass star formation regions.]
Without S-bearing species
Without N-bearing species
Carbon chains
N-bearing species
O-bearing species
S-bearing species
Population diagrams

- Local thermodynamical equilibrium (LTE)
- Optically thin lines
- Negligible CMB
- Size of the emission

\[ N_u = W \times \frac{8\pi k \nu^2}{hc^3 A_{ul}} \times C_\tau \]

\[ \ln \frac{N_u}{g_u} = \ln N_{\text{tot}} - \ln Q(T_{ex}) - \frac{E_u}{kT_{ex}} \]