Dense core formation in the turbulent, magnetized Pipe Nebula

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Outline of the talk

1. The Pipe Nebula

2. Large-scale gas kinematic properties

3. The low-extinction dense core population

4. Conclusions and perspectives
The Pipe Nebula: a molecular cloud with low star formation efficiency

- In the Ophiuchus region, low latitude; observable with IRAM and ALMA

- Nearby: 163±5 pc (Dzib+18, Gaia DR2)

- Star formation limited to the B59 region
Strong magnetic field

- Overall morphology: B-lines perpendicular to the Pipe filament on 20 pc scale
- Dispersion is largest in B59, and smallest in the Bowl
- Projected magnetic field intensity based on Davis-Chandrasekhar-Fermi: 17, 30, and 65 μG in B59, Stem, and Bowl (Alves+08)

Franco+10, polarization angles on an extinction map
The dense core mass function of the Pipe Nebula

- Dense core population identified based on wavelet decomposition in 2MASS extinction map (Lombardi+06)
- Genetic link between the Initial Mass Function and the Core Mass Function (Motte+98, Alves+07)
- Core-to-star formation efficiency = 0.40±0.20
- Generalized to Gould Belt star forming clouds (HGBS Herschel key program, André+10, Könyves+15)
New Observations

Large-scale $^{12}$CO(1-0) map with IRAM-30m
A large $^{12}$CO(1-0) map of a strongly dynamical, magnetized region

- Field of view located in a region where two velocity structures, proposed to be converging flows (Muench+07, Frau+10)
- The largest $^{12}$CO(1-0) map (0.5x0.7deg or 1.4pc x 2.0pc) at 22" (~3500 au) of the Pipe Nebula
- $A_V$ covering 0.5-5 mag over the field of view
- Complemented by pointed, multi-line observations of eight cores candidates from Rathborne+09 catalog: $^{13}$CO(1-0), $^{12}$CO(2-1), $^{13}$CO(1-0), C$^{18}$O(1-0)

- **Primary aims**
  - Analyse the orientation of structures with respect to magnetic fields
  - Determine the physical conditions and properties of dense cores in the region of converging flows

Extinction map, Hasenberger+18, based on Herschel+Planck

Column density $N(H_2)$ computed from extinction map of Hasenberger+18
Connected, large-scale velocity components

- Two velocity components (~3.5 and 5.0 km/s)
  - known from Onishi+99
  - Identified as converging flows (Muench+07, Frau+10)
- Connected in velocity space
- **Field of view in an interaction region**
A wealth of small-scale structures in velocity channels

- Large scales (FoV=1.4pcx2pc)
  - Velocity component at 6.0 km/s: almost parallel to $B_{\text{proj}}$
  - Velocity component at 3.5 km/s: brightest and unrelated to $B_{\text{proj}}$

- Small scales
  - Elongated structures are visible in most velocity channels, from 2.5 to 7.5 km/s
  - Eye-identification in velocity channels as elongated (aspect ratio > 2), structures spanning > 4 channels
  - Narrow filamentary structures: FWHM down to 0.06 pc

Intensity ($K$) at a given velocity (km/s). Magnetic field orientation indicated by a purple line
Structures in transitions

- Preliminary results
  - low-brightness structures, rather aligned with $B_{\text{proj}}$
  - 50% aligned or perpendicular
  - 50% neither aligned nor perpendicular

➢ Probing the transition from aligned to perpendicular?

Intensity ($K$) at a given velocity (km/s). Magnetic field orientation indicated by a purple line.
A new estimate for the magnetic field intensity

- **Skalidis+21**, magnetic field intensity:

  \[ B_0 = 123 \mu G \sqrt{2\pi} \left( \frac{\rho}{3.04 \times 10^{-21} \text{g cm}^{-3}} \right)^{1/2} \left( \frac{\delta V}{1.70 \times 10^5 \text{cm/s}} \right) \left( \frac{3.65^\circ}{\delta \phi} \right)^{1/2} \]

  - Uncertainty due to measures = 5 \( \mu \text{G} \)

- **Ostriker+01**, Mach number:

  \[ M = 2.39 \left( \frac{\delta \varpi}{1.7 \times 10^5 \text{cm/s}} \frac{2.97 \times 10^4 \text{cm/s}}{c_s} \right)^{1/2} \]

  - Uncertainty due to measures = 0.57

- Region with a medium to strong magnetic field

*Franco+10, polarization angles on an extinction map*
 Variety of line profiles
- Multiple velocity components in C$^{18}$O(1-0): RAT43, RAT49, RAT51
- Broad $^{12}$CO emission with undetected counterparts in $^{13}$CO and C$^{18}$O: RAT51, RAT54, RAT56, RAT57
- Extended $^{12}$CO with weak $^{13}$CO and undetected C$^{18}$O: RAT46, RAT55

 Dense and/or evolved gas tracers not detected: HCN and N$_2$H$^+$

➢ Are these local maxima of extinction really dense cores or false positives?
Gas column density estimations

- Multi-component Gaussian fit to C\textsuperscript{18}O(1-0) emission line profiles
- Simplifying assumptions
  - Assuming same T\textsubscript{ex} for all lines and homogeneous along line of sight
  - Gaussian C\textsuperscript{18}O opacity profile
  - No fractionation: \textsuperscript{12}CO/\textsuperscript{13}CO=70, \textsuperscript{12}CO/C\textsuperscript{18}O=500, \textsuperscript{13}CO/C\textsuperscript{18}O=7
- Results
  - C\textsuperscript{18}O(1-0) center line opacity: 0.03±0.02 < tau\textsubscript{18} < 0.64±0.04
  - \textsuperscript{12}CO column density: 7.1±2.4 \times 10\textsuperscript{15} < N(C\textsuperscript{18}O)x500[cm\textsuperscript{-2}] < 8.8±0.6 \times 10\textsuperscript{17}
  - CO/H=8.3\times10\textsuperscript{-5}; N\textsubscript{H} = 8.6\times10\textsuperscript{19} to 1.1\times10\textsuperscript{22} cm\textsuperscript{-2} or A\textsubscript{V}=0.05 to 5.7 mag
  - Core sample not representative of usual cores (A\textsubscript{V}~10 mag): young starless cores or transients?

\begin{center}
\includegraphics[width=\textwidth]{extinction_map.png}
\end{center}
Implication to the CMF

- High uncertainties on dense cores masses estimated from dust extinctions

- Implications to the break of the CMF!
Conclusions and perspectives

- First large-scale map 1.4pc x 2.0 pc at 22'' angular resolution of a highly dynamic, non star-forming region in the Pipe molecular cloud
- Two velocity components: first clear evidence of connection in velocity space
- Wealth of small-scale, elongated features, in \(^{12}\)CO(1-0) channel maps
  - Preliminary results from eye-inspection in x-y-v cubes: ~40% aligned, ~10% perp, ~50% neither aligned or perp
  - Probing the formation of filamentary structures in the interaction region two (converging ?) flows
- Dense cores from previous studies
  - \(A_V\) from 0.05 to 5.7 mag for each velocity component separately: extinction peaks and projection effects
  - Transient structures?

- Characterisation of the filaments (density estimations, large-scale coherence)
- Dense core candidates
  - Constrain evolutionary stage with early/late type species (see also Frau+12)
  - New estimates of the mass from dust and gas

Thank you for your attention