Herschel Observations of Gould Belt Cores and Filaments

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Part of Taurus
SPIRE 250 μm

Workshop on Dense Cores – Monterey – 28 July 2014

Palmeirim+ 2013
Outline:

• « Universality » of the filamentary structure of the ISM

• Census of prestellar cores

• The key role of filaments in the core formation process

• Implications, open issues, and conclusions


Herschel GB survey IC5146 Arzoumanian et al. 2011

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The Herschel Gould Belt Survey

SPIRE/PACS 70-500 μm imaging of the bulk of nearby (d < 0.5 kpc) molecular clouds (~ 250 deg²), mostly located in Gould’s Belt.
- Complete census of prestellar cores and Class 0 protostars.

Motivation: Key issues on the early stages of star formation

- What generates prestellar cores and governs their evolution?
- Nature of relationship between the prestellar CMF & the IMF?
Herschel has revealed a “universal” filamentary structure in the cold ISM.

Pipe
Peretto + 2012

Taurus
Palmeirim + 2012
Kirk + 2012

Polaris
Ward-Thompson + 2010
Miville-Deschênes + 2010

Aquila
Könyves + 2010

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Structure of the cold ISM prior to star formation

Gould Belt Survey
PACS/SPIRE // mode
70/160/250/350/500 µm

Polaris flare
translucent cloud:
non star forming

~ 5500 M☉ (CO+HI)
Heithausen & Thaddeus ‘90

~ 13 deg² field

Miville-Deschênes et al. 2010
Ward-Thompson et al. 2010
Men’shchikov et al. 2010
André et al. 2010

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Evidence of the importance of filaments prior to Herschel

Taurus
IRAS (100-60/100/12 µm) composite

Infrared Dark Clouds
Spitzer (3.6/8/24 µm) composite

Abergel, Boulanger et al. 1994
See also: Schneider & Elmegreen 1979; Mizuno et al. 1995; Johnstone & Bally 1999; Hartmann 2002; Hatchell et al. 2005; Goldsmith et al. 2008; Myers 2009 …

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The observed filaments are reminiscent of those found in cloud simulations with large-scale turbulence.
Evidence of much fainter filaments + high degree of universality with Herschel

Taurus B211 filament: M/L ~ 50 M_☉/pc
P. Palmeirim et al. 2013

Musca filament:
M/L ~ 30 M_☉/pc
N. Cox et al in prep.

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Evidence of much fainter filaments + high degree of universality with *Herschel*

Musca filament: M/L ~ 30 M⊙/pc
N. Cox et al in prep.

- Accretion flows along field lines into the main filaments?

Taurus B211 filament: M/L ~ 50 M⊙/pc
P. Palmeirim et al. 2013

Polarization vectors overlaid on *Herschel* images

*Pereyra & Magelhaes 2004*

Optical Polarization
Heyer+2008
Heiles 2000

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Resolving the structure of filaments with *Herschel*

Taurus B211/3 filament
SPIRE 250 µm

Plummer-like density profile (p = 2):

\[
\rho(r) = \frac{\rho_c}{[1 + (r/R_{\text{flat}})^2]}
\]

with \( R_{\text{flat}} \sim 0.05 \) pc

Diameter of flat inner plateau:

\[
2R_{\text{flat}} \sim 0.1 \text{ pc}
\]
Filaments have a characteristic inner width $\sim 0.1$ pc

Network of filaments in IC5146

Statistical distribution of widths for $>270$ nearby filaments

- IC5146
- Orion B
- Aquila
- Polaris
- Ophiuchus
- Taurus
- Pipe
- Musca

Example of a filament radial profile

- Inner radius $\sim 0.05$ pc
- Outer radius $0.5$ pc
- Beam
- Background

D. Arzoumanian et al. 2011 + PhD thesis

[see also Alves de Oliveira+2014 for Chamaeleon;
Some variations along each filament: Ysard+2014]

Strong constraint on the formation and evolution of filaments

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Filaments due to large-scale supersonic turbulence?

Filament width ~ 0.1 pc: ~ sonic scale of interstellar turbulence?

- Linewidth-Size relation in clouds (Larson 1981)
  \[ \sigma_v(L) \propto L^{0.5} \]

- Simulations of turbulent fragmentation

- Corresponds to the typical thickness expected for shock-compressed layers in HD

- Filaments from a combination of MHD turbulent compression and shear; width set by the dissipation scale of MHD waves? (Hennebelle 2013)
Dense cores form primarily in filaments

Morphological Component Analysis:

**Herschel** Column density map

Cores + Curvelet component \((\text{H}_2/\text{cm}^2)\)

Filaments

(P. Didelon based on Starck et al. 2003)
Examples of *Herschel* prestellar cores in Aquila

- **Core** = single star-forming entity  
  (Need to resolve ~ 0.01-0.1 pc)
- **Starless** = no central proto★
- **Prestellar** = bound & starless

[ For definitions, see: 
Di Francesco et al. 2007, PPV  
Ward-Thompson et al. 2007, PPV  
Bergin & Tafalla 2007, ARA&A ]

Core extraction with *getsources* (Men’shchikov+2012)

Core extraction with *csar* (J. Kirk+2013)

Könyves et al. 2010 + in prep.

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Using/comparing different techniques to trace/quantify the filamentary structure and its connection with cores

Morphological Component Analysis
curvelets + wavelets
(P. Didelon based on Starck et al. 2003)

getfilaments decomposition
(Men’shchikov 2013)

Skeleton of the filament network traced with the DisPerSE algorithm (Sousbie 2011)

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Quantifying the connection between filaments & cores

Aquila

0.1 pc filament “footprints”

▲: Prestellar cores

Könyves et al., in prep.
~ 75 ±15 \% of prestellar cores form in filaments, above a column density threshold \(N_{\text{H}_2} \geq 7 \times 10^{21} \text{ cm}^{-2}\) => \(A_v \geq 7\)

\[\Sigma_{\text{threshold}} \sim 150 \, M_\odot/\text{pc}^2\]

**Examples of *Herschel* prestellar cores (\(\Delta\))**

André et al. 2010, Könyves et al. 2010 + in prep

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Strong evidence of a column density “threshold” for the formation of prestellar cores

Distribution of background column densities for the Aquila prestellar cores

In Aquila, ~90% of the prestellar cores identified with *Herschel* are found above 

\[ A_v \sim 7 \quad \Leftrightarrow \quad \Sigma \sim 150 \, M_\odot \, \text{pc}^{-2} \]

Könyves et al. in prep

André+2014 PPVI

See also:

Onishi+1998

Johnstone+2004
Distribution of mass in the parent cloud and background-dependent completeness imply that this threshold is very significant!

Cumulative mass fraction ($> N_{H2}$)

\[ \sim 85\% \text{ of the mass} \quad \sim 15\% \text{ of the mass} \]

Column density, $N_{H2}$ [cm$^{-2}$]

Aquila

Completeness curves vs. background $A_v$

$A_v \sim 7$

$A_v \sim 5$

$A_v \sim 20$

Könyves et al. in prep

(See also Lada+2010 for similar mass fraction plots based on extinction)

Completeness when $A_v$ because “cirrus noise” fluctuations (cf. Gautier et al. 1992)

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Filaments are expected to be:

- gravitationally unstable if $M_{\text{line}} > M_{\text{line, crit}}$
- unbound if $M_{\text{line}} < M_{\text{line, crit}}$

$M_{\text{line, crit}} = 2 c_s^2 / G \sim 16 M_\odot / \text{pc}$ for $T \sim 10 \text{K}$

- $\Sigma$ threshold $\sim 160 M_\odot / \text{pc}^2$
- $\rho$ threshold $\sim 1600 M_\odot / \text{pc}^3$

Simple estimate:

$M_{\text{line}} \propto N_{\text{H}_2} \times \text{Width} \sim 0.1 \text{ pc}$

Unstable filaments highlighted in white in the $N_{\text{H}_2}$ map of Aquila

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André et al. 2010

Interpretation of the threshold: $\Sigma$ or M/L above which interstellar filaments are gravitationally unstable
**Toward a new paradigm for ~ M\(_\odot\) star formation?**


1) Large-scale MHD supersonic ‘turbulence’ generates filaments

2) Gravity fragments the densest filaments into prestellar cores

\[
\frac{M}{L} > M_{\text{line, crit}} = 2 \frac{c_s^2}{G}
\]

Protostellar Cores

Polaris – *Herschel* SPIRE 250 µm

Taurus B211/3 – *Herschel* 250 µm
Filament fragmentation may account for the peak of the prestellar CMF and the “base” of the IMF

Core Mass Function (CMF) in Aquila Complex

- CMF peaks at $\sim 0.6 \, M_\odot \approx$ Jeans mass in marginally critical filaments
- Close link of the prestellar CMF with the stellar IMF: $M_\star \sim 0.3 \times M_{\text{core}}$
- Characteristic stellar mass may result from filament fragmentation

Jeans mass:

$$M_{\text{Jeans}} \sim 0.5 \, M_\odot \times (T/10 \, \text{K})^2 \times \left(\frac{\Sigma_{\text{crit}}}{160 \, M_\odot \, \text{pc}^{-2}}\right)^{-1}$$
Estimates of prestellar core lifetimes in Aquila

Estimated lifetime versus core density

$\begin{align*}
\text{Lifet ime of cores } & > n_{\text{H}_2} \text{ [yr]} \\
\text{Average volume density } n_{\text{H}_2} \text{ [cm}^{-3}] & \\
10^4 & \rightarrow 10^7 \\
10^5 & \\
10^6 & \\
10^7 &
\end{align*}$

$\Delta$ Aquila prestellar cores

Literature data

$t = 10 \times t_{\text{ff}}$

$t = t_{\text{ff}}$

$\sim 450 \text{ Herschel prestellar cores}$

$t_{\text{pre}} = 1 \pm 0.3 \text{ Myr}$

$\sim 3\text{-}4 t_{\text{ff}}$

$\sim 200 \text{ Herschel Class0/ClassI protostars}$

(t $\sim 0.5 \text{ Myr}$)

$\sim 800 \text{ Spitzer ClassII YSOs}$

[Dunham+2013]

(t $\sim 2 \text{ Myr}$)

Könyves et al. in prep.

cf. Lee & Myers 1999

Ward-Thompson et al. 2007 PPV (literature data)
Importance of the threshold on galactic scales: A universal star formation law above the threshold?

Star Formation Rate ($M_\odot$/yr)

$\approx 4.5 \times 10^{-8} \times M_{\text{dense}} (M_\odot) = \epsilon_{\text{core}} \times f_{\text{pre}} \times M_{\text{dense}} / t_{\text{pre}} \approx 0.3 \times 0.15 \times M_{\text{dense}} (M_\odot) / 10^6$

$M_{\text{dense}} = \text{Mass of dense gas above the threshold (A}_V > 8 \text{ or } n_{\text{H}_2} > 2.5 \times 10^4 \text{ cm}^{-3})$

HCN  Gao & Solomon 2004

Lada et al. 2012

André+2014 PPVI; Könyves+, in prep
Origin of the characteristic width of filaments?

Paradox: Dense filaments should radially contract!

Central column density $N_{\text{H}_2}$ [cm$^{-2}$]

Filament width (FWHM) [pc]

Stability parameter $M_{\text{line}}/M_{\text{line,Crit}}$

0.1

1.0

10.0

D. Arzoumanian et al. 2011 + PhD thesis

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Key: Evidence of accretion of background material (striations) along field lines onto self-gravitating filaments

Example of the B211/3 filament in the Taurus cloud ($M_{\text{line}} \sim 54 \text{ M}_\odot/\text{pc}$)
Palmeirim et al. 2013 (see also H. Kirk, Myers ea 2013 for another example: Serpens-South)

Estimate of the mass accretion rate:
$\dot{M}_{\text{line}} \sim 25-50 \text{ M}_\odot/\text{pc}/\text{Myr}$

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Accretion-driven MHD turbulence can prevent the radial contraction of dense filaments

Model of accreting filaments

Balance between accretion-driven turbulence (Klessen & Hennebelle 2010) and dissipation of MHD turbulence due to ion-neutral friction

« Dynamical » equilibrium with \(<width> \sim 0.1 \text{ pc}\)

D. Arzoumanian et al. 2011 + PhD thesis
+ Hennebelle & André 2013 (see also Heitsch 2013)

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Evidence of velocity-coherent substructures or “fibers” in the Taurus B211/B213 filament

Bundle of 35 velocity-coherent « fibers » (~ 0.5 pc long) detected in C$^{18}$O and making up the main filament

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The Taurus filament’s fibers are also seen by *Herschel*

Hacar et al. (2013)’s $^{18}$O « fibers » overlaid on *Herschel* 250 µm image (Palmeirim et al. 2013)

Filtered 250 µm image showing the fine structure of the Taurus B211/3 filament

Filter 250 µm image showing the fine structure of the Taurus B211/3 filament

The B211/3 « fibers » may possibly be the manifestation of accretion-driven turbulence in the main filament (?)
Conclusions: A filamentary paradigm for star formation?

- Herschel results suggest core formation occurs in 2 main steps:
  1) ~ 0.1 pc-wide filaments form first in the cold ISM, probably as a result of the dissipation of large-scale MHD turbulence;
  2) The densest filaments then fragment into prestellar cores via gravitational instability above a critical (column) density threshold $\Sigma_{th} \sim 150 \, M_\odot \, pc^{-2} \Leftrightarrow A_V \sim 7 \Leftrightarrow n_{H_2} \sim 2 \times 10^4 \, cm^{-3}$

- Filament fragmentation appears to produce the peak of the prestellar CMF and may account for the « base » of the IMF

- This scenario may possibly account for the global rate of star formation in dense molecular gas on galaxy-wide scales