Highlights from the *Herschel* Gould Belt survey: Toward a Unified Picture for Star Formation on GMC scales?

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![Image of Herschel telescope with labels: Near Aquila, Far, Herschel Gould Belt Survey, GOODS-N HERMES, SPIRE SAG 3, PACS, HERSCHEL Gould Belt Survey.](image)
Outline:

• « Universality » of the filamentary structure of the ISM

• The key role of filaments in the star formation process

• Implications and future prospects


Herschel GB survey IC5146 Arzoumanian et al. 2011
Filamentary structure of the cold ISM prior to SF

Gould Belt Survey
*Herschel* // mode
70/160/250/350/500 μm

Polaris flare
translucent cloud
(d ~ 150 pc)

~ 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
A&A vol. 518

SPIRE 250 μm image

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Evidence of the importance of filaments prior to *Herschel*
but … much fainter filaments + universality with *Herschel*

**Extinction map of Musca**

Cambrésy 1999

See also:
Schneider & Elmegreen 1979;
Abergel et al. 1994; Johnstone & Bally 1999;
Hatchell et al. 2005; Goldsmith et al. 2008; Myers 2009 …
+ Many numerical simulations

**Musca**

*Herschel*

250 μm

N. Cox et al., in prep. - See Poster B-37

Polarization vectors overlaid on *Herschel* image of Musca

N. Cox et al. + Pereyra & Magelhaes 2004

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Very common pattern: main filament + network of perpendicular striations or “sub-filaments”

Taurus B211/3 filament: $M/L \sim 50 M_\odot/pc$

P. Palmeirim et al. 2013

- Suggestive of accretion flows into the main filaments

DR21 in Cygnus X:

$M/L \sim 4000 M_\odot/pc$

M. Hennemann, F. Motte et al. 2012

Also Schneider ea. 2010, Csengeri ea. 2011

Optical Polarization
Heyer et al. 2008
Heiles 2000

PACS 70μm (Jy/pix)

HOBYS
70 μm

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Characterizing the structure of filaments with *Herschel*


Taurus B211/3 filament
SPIRE 250µm

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Filaments have a characteristic inner width ~ 0.1 pc

D. Arzoumanian’s PhD thesis
See Poster B-31

Using the DisPerSE algorithm (Sousbie 2011) to trace the crest of each filament

Statistical distribution of widths for > 270 filaments

Distribution of Jeans lengths
$[\lambda_J \sim c_s^2/(G\Sigma)]$

IC5146
Orion B
Aquila
Polaris
Ophiuchus
Taurus
Pipe
Musca

Strong constraint on the formation and evolution of filaments

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Filament width \( \sim 0.1 \) pc \( \sim \) sonic scale of ISM turbulence

Filaments due to dissipation of large-scale turbulence?

- \( \sigma_v(L) \propto L^{0.5} \)
- Corresponds to the typical thickness of shock-compressed structures in the turbulent fragmentation scenario
- Filaments from a combination of MHD turbulent compression \textit{and} shear; width set by the energy dissipation scale (Hennebelle 2013, A&A, 556, A153)

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At low densities, consistent with model of polytropic filaments \( (P \sim \rho^\gamma \text{ with } \gamma \sim 0.8) \) in pressure equilibrium with a typical ISM pressure \( P_{\text{ext}}/k_B \sim 5 \times 10^4 \text{ K cm}^{-3} \) (Inutsuka, in prep.)

See also Fischera & Martin 2012, A&A, 542, A77 for a similar model for isothermal filaments

**Reference**

D. Arzoumanian’s PhD thesis

**Caption**

Filament width vs. Column density

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

Stability parameter \( M_{\text{line}}/M_{\text{line,Crit}} \)

Thermal Jeans length \( \lambda_J \sim c_s^2/(G \Sigma) \)
Evidence of accretion of background material (striations) onto self-gravitating filaments

Example of the B211/3 filament in the Taurus cloud ($M_{\text{line}} \sim 54 \, M_\odot/\text{pc}$)
Palmeirim et al. 2013

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

CO observations from Goldsmith et al. 2008

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Filament width vs. Column density

At high densities, consistent with a model of accreting filaments (Hennebelle & André 2013, A&A)

➤ Balance between ‘accretion-driven turbulence’ (Klessen & Hennebelle ’10) and dissipation of MHD turbulence due to ion-neutral friction

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

Arzoumanian et al. 2011
D. Arzoumanian’s PhD thesis

See also Heitsch 2013a,b
\(~75\%\) of prestellar cores form in filaments, above a column density threshold \(N_{\text{H}_2} \geq 7\times10^{21}\ \text{cm}^{-2}\) \(\Leftrightarrow\) \(A_v \geq 8\) 

\( \Sigma_{\text{threshold}} \sim 130\ \text{M}_\odot/\text{pc}^2\)
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 $A_v \sim 8 \Rightarrow \Sigma \sim 130 \, M_{\odot} \, pc^{-2}$

Könyves et al. in prep
André et al. IAU270 (astro-ph/1309.7762)

See also (for YSOs):
Heiderman et al. 2010
Lada et al. 2010

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Interpretation of the threshold: $\Sigma$ or $M/L$ above which interstellar filaments are gravitationally unstable

- Unstable if $M_{\text{line}} > M_{\text{line, crit}}$
- Unbound if $M_{\text{line}} < M_{\text{line, crit}}$

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

$\Sigma$ threshold $\approx 160 M_\odot / \text{pc}^2$

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

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Filament fragmentation may account for the peak of the prestellar CMF and the “base” of the IMF

Core Mass Function (CMF) in Aquila Complex

> 400 prestellar cores in Aquila
(cf. Talk by V. Könyves on Thursday)

Jeans mass:

\[ M_{\text{Jeans}} \approx 0.5 M_\odot \times (T/10 \text{ K})^2 \times (\Sigma_{\text{crit}}/160 M_\odot \text{pc}^{-2})^{-1} \]

- Good mapping between core mass and stellar system mass: \( M_* = 0.3 \times M_{\text{core}} \)
- CMF peaks at \( \sim 0.6 M_\odot \approx \) Jeans mass in marginally critical filaments
- Suggests prestellar cores at the peak of the CMF result from gravitational fragmentation of filaments

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Toward a new paradigm for star formation?

- *Herschel* results suggest **star formation occurs in 2 main steps:**
  1) 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 \( \Sigma_{th} \sim 150 \text{ } \text{M}_\odot \text{pc}^{-2} \iff A_V \sim 8 \iff n_{\text{H}_2} \sim 2 \times 10^4 \text{ } \text{cm}^{-3} \)

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

- Massive star formation tends to occur in « ridges » (\( A_V > 100 \)) at the junctions of supercritical filaments (Talk by F. Motte on Friday)

- This scenario may possibly account for the global rate of star formation on galactic scales

See related chapter for « Protostars & Planets VI »

(See also astro-ph/1309.7762)

by André, Di Francesco, Ward-Thompson, Inutsuka, Pudritz, Pineda
A universal star formation law above the threshold?

\[ \text{SFR (M}_\odot/\text{yr}) \approx 4.5 \times 10^{-8} \times M_{\text{dense}}(M_\odot) \]

\[ = \varepsilon_{\text{core}} \times f_{\text{pre}} \times M_{\text{dense}} / t_{\text{pre}} \approx 0.3 \times 0.15 \times M_{\text{dense}}(M_\odot) / 10^6 \]

Herschel results on Aquila prestellar cores

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

Lada et al. 2012

HCN  Gao & Solomon 2004

\[ A_V > 8 \text{ mag} \quad \text{Lada et al. 2010} \]

\[ \text{normal spirals} \]

\[ \text{galaxies} \]

\[ \text{ULIRGs} \]