Dust emission of the Galactic ISM as seen by Planck and Herschel.

Observed properties of interstellar filaments

Aquila
Star forming molecular cloud

15 pc at 260 pc

Doris Arzoumanian
(JSPS fellow, Nagoya University)

02/05/2017
EAO Seminar, Hilo, Big Island
Dust emission of the Galactic ISM as seen by Planck and Herschel

- PhD thesis at CEA Saclay, France (November 2009-2012)
  "Characterizing interstellar filaments as revealed by the Herschel Gould Belt survey: Insights into the initial conditions for star formation" PhD supervisor: Philippe André
- Post-Doc at IAS Orsay, France (2013 -2015)
  "Analysis of the polarized emission from the Galactic dust observed by Planck towards interstellar filaments"
  Working in the group of François Boulanger, part of the ERC MISTIC project
- Currently JSPS fellow at Nagoya University
  "Combining theory and observations"
  In the group of Shu-ichiro Inutsuka

Aquila
Star forming molecular cloud

15 pc at 260 pc

4 deg

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IC5146 molecular cloud
Optical image

Cocoon Nebula

Dust emission
Herschel

Optical image
Molecular clouds seen in extinction

5 pc at 460 pc

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Evolutionary sequence

Formation of solar-type stars

Evolutionary sequence well established but physics of early stages still unclear (McKee & Ostriker 2007, Shu et al. 1987)

Open questions:

- What generates prestellar cores in molecular clouds and governs their evolution?
- What sets the mass of star forming cores and stars?
- What is the link between star formation and the structure of the parent clouds

(Lada 1987, André et al. 2000)
**Herschel** observes the peak emission of the cold dust

**Herschel** bands cover the peak dust emission and are essential for gas column density and dust temperature determination.

Dust temperature range probed with **Herschel**

\[ \sim 35K > T_{\text{dust}} > 7K \]

\[ I_\nu = B_\nu(T_\text{dust}) \tau_\nu \]

\[ \tau_\nu = \kappa_\nu \sum \]

\[ \kappa_\nu = 0.1 (\nu/1000 \text{ GHz})^8 \text{ cm}^2/\text{g} \]
Gas column density and dust temperature maps (e.g. IC5146)

PACS & SPIRE
160 – 500 µm
4 λ SED fitting (pixel by pixel) with a modified blackbody function

Maps at 36.3” resolution of SPIRE 500 µm

Column density map

$N_{\text{H}_2}$(cm$^{-2}$)

Dust temperature map

$T_{\text{dust}}$(K)

Cocoon Nebula

Filaments

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Spatial distribution of prestellar cores within the densest Filaments

Sources extracted with *getsources* Men’shchikov et al. 2010, (2012)

Column density map of IC5146

- **Prestellar cores**
- **Protostars**

- Cocoon Nebula
- Northern streamer
- Southern streamer
- BD+46 3474

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Omnipresence of filamentary structures both in star forming regions and in quiescent clouds

*Herschel* probes simultaneously the large scale structures (~10 pc) and the small scale prestellar cores (~0.01 pc) of the nearby interstellar medium (ISM)

André et al., Bontemps et al., Könyves et al., Men’shchikov et al., Miville-Deschênes et al. 2010

**Prestellar cores**

- **Aquila** (Active star formation)
- **Polaris** (quiescent, no star formation)

*Herschel* 250 µm

3 pc at 260 pc

2 pc at 150 pc
Star formation along dense filaments

- Interstellar filaments are observed in star forming and quiescent clouds (e.g., André et al. 2010. Miville-Deschenes et al. 2010, Juvela et al. 2012)
- Dense filaments are the main sites for star formation (André et al. 2010, 2014)
- Filaments are produced by (all kinds of) numerical simulations (e.g., Hennebelle et al. 2008, Federrath et al. 2010, Mac Low & Klessen 2004, Inutsuka 2015)

>> Filament formation prior to any star forming activity
>> Insights into the initial conditions for star formation?

MHD simulation (Courtesy: Kazunari Iwasaki)

Herschel observations of submm dust emission

IC5146 molecular cloud

Star forming cores

Arzoumanian et al. 2011

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Questions:

How do interstellar filaments form and evolve in a magnetohydrodynamical turbulent interstellar medium?

What is the role of interstellar filaments in the star formation process?

As an observer…

What are the observed properties of interstellar filaments?

• Column density and temperature distributions of the filaments observed with *Herschel* dust continuum observations
• Signature of the magnetic field structure from *Planck* dust polarization observations
• Velocity structure of interstellar filaments derived from Molecular line observations

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Filament properties as derived from *Herschel* observations

Taurus B211/13 filament

$N_{H_2}$ [cm$^{-2}$]

$1$ pc

$0.1$ pc

Resolution 18'' ~ 0.02pc at 140pc

Arzoumanian et al. 2011, Palmeirim et al. 2013

T$_{dust}$ [K]

$1$ pc

$T_{dust}$ [K]

$16$

$15$

$14$

$13$

$12$

$11$

$-1.0$ $-0.5$ $0.0$ $0.5$ $1.0$

Radius [pc]

Log-Log scale

Inner radius

Logarithmic scale

Outer radius

Linear scale

Gaussian fit

Background

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Filament Mass per unit length: Stability of cylindrical filaments

Taurus
$N_{\text{H}_2}$ [cm$^{-2}$]

B211/13 filament
Resolution 18'' $\sim$ 0.02pc at 140pc

Thermally supercritical filament with $M_{\text{line}} > M_{\text{line,crit}}$ are unstable for radial collapse and gravitational fragmentation (Inutsuka & Miyama 1997)

The critical (thermal) mass per unit length is $M_{\text{line,crit}} = 2c_s^2/G$, where $c_s$ is the sound speed (unmagnetized hydrostatic equilibrium solution) (Stodolkiewicz 1963, Ostriker 1964)

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Filament Mass per unit length: Stability of cylindrical filaments

Runaway collapse of thermally supercritical filaments with $M_{\text{line}} > 2M_{\text{line,crit}}$

Thermally supercritical filament with $M_{\text{line}} > M_{\text{line,crit}}$ are unstable for radial collapse and gravitational fragmentation (Inutsuka & Miyama 1997)

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Radial profiles and masses per unit length of filaments derived from *Herschel* column density maps

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

- **Orion**: Thermally supercritical, $M_{\text{line}} \gg M_{\text{line,crit}}$, 0.5 pc at 400 pc, $95 M_\odot/\text{pc}$
- **Musca**: Thermally ~critical, $M_{\text{line}} \approx M_{\text{line,crit}}$, 2 pc at 200 pc, $20 M_\odot/\text{pc}$
- **Polaris**: Thermally subcritical, $M_{\text{line}} \ll M_{\text{line,crit}}$, 0.5 pc at 150 pc, $1 M_\odot/\text{pc}$

All three filaments have similar inner widths $\sim 0.1$ pc
Filamentary structures of nearby molecular clouds as seen by HERSHEYEL Gould Belt Survey.

- Taurus
  - Palmeirim + 2013
  - Marsh + 2015
- Pipe
  - Peretto + 2012
- Orion B
  - N. Schneider + 2013
- Musca
  - N. Cox + 2015
- IC5146
  - Arzoumanian + 2011
- Aquila
  - Könyves + 2010, 2015
  - André + 2010

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Tracing the filamentary networks observed in the ISM

Algorithms and methods to identify/trace filaments in 2D maps:
DisPerSE algorithm (Sousbie 2011), MCA (Starck et al. 2003), getfilaments (Men’shchikov 2013)
Rolling Hough Transform (Clark et al. 2014), FilFinder (Koch & Rosolowsky 2015)

Examples on Herschel maps

Getfilaments + DisPerSE

FilFinder + DisPerSE

Chamaeleon

Aquila

Könyves et al. 2015

Koch & Rosolowsky 2015

Arzoumanian et al. 2011

MCA + DisPerSE

IC5146

Minimum curvature map derived from the Hessian matrix analysis

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Interstellar filaments share a common inner width of $0.1 \text{pc}$ while they span a wide range in column density.

Arzoumanian et al. 2011, 2013, André et al 2014

Herschel observations of IC5146 molecular cloud

Unbound quiescent filaments  Self-gravitating star-forming filaments

~ $0.1 \text{ pc}$
Filament formation from the dissipation of supersonic interstellar turbulence?

Linewidth-Size relation in clouds (Larson 1981)

\[ \sigma_V(L) \propto L^{0.5} \]

0.2 km/s sound speed

0.1 pc Sonic scale of the cold ISM (Goodman et al. 1998, Falgarone et al. 2009, Federrath et al. 2010)

Sonic scale: transition scale between supersonic and subsonic turbulence

Unbound quiescent filaments
Self-gravitating star-forming filaments

Central column density \( N_{H_2} \) [cm\(^{-2}\)]
Filament width (FWHM) [pc]

Thermal Jeans length \( \lambda_J \sim c_s^2/(G\Sigma) \)

Polaris cloud

HGBS André+ 2010

Arzoumanian et al 2011

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Velocity dispersion of interstellar filaments

Two regimes for filaments
Subcritical and unbound / supercritical and self gravitating

N$_2$H$^+$(1-0) spectra towards 2 filaments in Aquila

(0.24+-0.01) km/s
1.2 x 10$^{22}$ cm$^{-2}$

(0.64+-0.01) km/s
2.1 x 10$^{23}$ cm$^{-2}$

$\sigma_{\text{tot}}^2 = \sigma_{\text{NT}}^2 + \sigma_T^2$

$M_{\text{line,crit}} = 2c_s^2/G \sim 16 M_\odot$/pc for T=10K, equivalent to $N_{\text{H}_2} \sim 8 \times 10^{21}$ cm$^{-2}$

Arzoumanian et al. 2013

Estimated mass per unit length $[M_\odot$/pc], $M_{\text{line}} = \Sigma W (W=0.1$pc)

Thermally subcritical
DR21
NGC2264C
IC5146
Aquila
Polaris

N$_2$H$^+$(1-0)

$C^{18}$O

Total velocity dispersion, $\sigma_{\text{tot}}$ [km/s]

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

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Hint of the evolution of supercritical filaments from their observed velocity dispersion?

Supercritical filaments are observed to be in nearly virial balance.

Increase of the total velocity dispersion with central column density for supercritical filaments driven by the accretion of matter?

(Klessen & Hennebelle 2010, Hennebelle & André 2013)

**Virial mass per unit length** (Fiege & Pudritz 2000)

\[
M_{\text{line,crit}} = 2c_s^2 / G
\]

\[
M_{\text{line,vir}} = 2\sigma_{\text{tot}}^2 / G
\]
Indirect evidence of accretion of surrounding material onto dense filaments

Example of the B211/B213 filament in the Taurus molecular cloud
Palmeirim et al. 2013, Shimajiri et al. in prep.

Low column density filaments or striations seem to be feeding the dense filament

CO observations from Goldsmith et al. (2008)
What about the magnetic field structure?

Information on the plane of the sky projected orientation of the magnetic field in the ISM derived from dust polarization observations
Why do dust grains emit linearly polarized light?

- Linear polarization results from non-spherical spinning dust grains, which precess around the ambient magnetic field (Davis & Greenstein 1951, Vaillancourt 2007)

\[ \text{B orientation} = \text{pol. direction} + 90^\circ \]

Maximal axis of inertia

- Aligned grains
- Polarized radiation
- Polarization of thermal radiation

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Why do dust grains emit linearly polarized light?

Dust polarization depends on (Lee & Draine 1985, Hildebrand 1983):
1) Dust properties (shape, size, composition),
2) Grain alignment efficiency with the local magnetic field
3) The structure of the magnetic field
Why do dust grains emit linearly polarized light?

Dust polarization depends on (Lee & Draine 1985, Hildebrand 1983):
1) Dust properties (shape, size, composition),
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3) The structure of the magnetic field

Derived quantities:
- Total polarized intensity \((P)\)
- Polarization fraction \((p=P/I)\)
- Polarization angle (orientation of \(\mathbf{B}\) field projected on the plane of the sky)

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Large scale magnetic field structure of the ISM derived from the dust polarized emission observed by Planck

Planck

1° resolution

Total intensity at 353 GHz, with plane-of-the-sky magnetic field ($B_{POS}$) orientation

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Planck intermediate results XIX
astro-ph1405.0871
Statistical analysis of the relative orientation between magnetic field and intensity structures observed by *Planck*

In molecular clouds, high column density structures/filaments appear to be perpendicular to the local $B_{\text{POS}}$, while fainter filaments are parallel to $B_{\text{POS}}$

*Planck* XXXV 2015 (1502.04123), XXXII 2014 (1409.6728)

Relative orientation between the angle of $B_{\text{POS}}$ and intensity structures on the plane of the sky

Total intensity map at 353GHz, blue contours: $I$ (3 & 6 MJy/sr), Resolution: 5’, black segments: $B_{\text{POS}}$ orientation, length $\sim$ polarization fraction, Resolution: 10’

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Statistical analysis of the relative orientation between magnetic field and intensity structures observed by *Planck*

In molecular clouds, high column density structures/filaments appear to be perpendicular to the local $B_{\text{POS}}$, while fainter filaments are parallel to $B_{\text{POS}}$

*Planck* XXXV 2015 (1502.04123), XXXII 2014 (1409.6728)

This trend is also observed in ten other clouds of the Gould Belt

*Planck* XXXV 2015 (1502.04123)

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Ordered magnetic field structure in molecular clouds

The observations suggest that, at the scales probed by Planck, the magnetic field is dynamically important in the formation of structures/filaments

*Planck* XXXII 2014 (1409.6728), XXXV 2015 (1502.04123)

Comparison with MHD numerical simulations (e.g., Falceta-Gonçalves et al. 2008, Soler et al. 2013) and with estimates of field strength from Chandrasekhar-Fermi method (e.g., Chapman et al. 2011)
Plane of the sky magnetic field orientation perpendicular to the long axis of high column density filaments

Suggesting filament formation from matter flow along magnetic field lines?

Optical polarization tracing the magnetic field orientation (Pereyra & Magalhaes 2004)

Planck total intensity at 353GHz (850μm) in MJy/sr
Segments: $B_{\text{POS}}$ length ~ polarization fraction ($p$) (10' resolution) Planck XXXIII 2016 (arXiv:1411.2271)
Variation of the polarization angle (i.e., orientation of $B_{\text{POS}}$) from the parent cloud to the filament

Polarization angle across the filaments (perpendicular to the major axis)

Beam: 0.2pc for Taurus, 0.3pc for Musca

Total intensity map at 353GHz (850 $\mu$m), Resolution: 5', black segments: orientation of $B_{\text{POS}}$, length ~ p, Resolution: 10'
Variations of the polarization angle and the polarization fraction: Insight on the 3D magnetic field structure in the filaments?

The polarization fraction depends on (Lee & Draine 1985, Hildebrand 1983):
1) Dust properties (shape, size, composition),
2) Grain alignment efficiency with the local magnetic field
3) The structure of the magnetic field

\[ p = \frac{P}{I} \]

Polarized intensity
\[ P = \sqrt{Q^2 + U^2} \]

\( I \): total intensity

Resolution of 5', 0.3pc at 200pc

Planck XXXIII 2015 (arXiv:1411.2271)
Polarization fraction across the Musca filament

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Variations of the polarization angle and the polarization fraction: Insight on the 3D magnetic field structure in the filaments?

The polarization fraction depends on (Lee & Draine 1985, Hildebrand 1983):
1) Dust properties (shape, size, composition),
2) Grain alignment efficiency with the local magnetic field
3) The structure of the magnetic field

The decrease of $p$ may be due to the 3D structure of $B$ in the filaments

>> higher resolution observations and theoretical modelling are needed

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Planck XXXIII 2015 (arXiv:1411.2271)

Polarization fraction across the Musca filament

The polarization fraction $p$ is defined as $p = P/I$.

Polarized intensity $P = \sqrt{Q^2 + U^2}$

$I$: total intensity

Resolution of 5', 0.3pc at 200pc

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Large and small scale magnetic field structures of the Orion A molecular cloud as inferred from Planck and JCMT/SCUBA2-POL2

BISTRO project 1st results

Ward-Thompson et al. 2017

Image: Herschel 250μm (18.2")
Drapery pattern: large-scale POS B-field orientation from Planck dust polarization at 850μm (5")

Image: SCUBA2 at 850μm (14.1")
Segments: small scale POS B-field from POL2 at 850μm (14.1")

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Summary

• *Herschel* and *Planck* observations reveal the ubiquity of interstellar filaments in the ISM

• “Two filament families”: subcritical / unbound and supercritical / self-gravitating
  - Common properties: inner width ~ 0.1 pc (origin?)
  - Wide range in length, column density, $M_{\text{line}}$

• Filament formation?
  - Prior to any star formation activity (*initial conditions for star formation?*)
  - Role of the dissipation of MHD interstellar turbulence (*origin of the 0.1pc-width?*)

• Evolution of self-gravitating filaments?
  - Gravitational fragmentation of supercritical filaments in star forming cores
  - Role of the magnetic field?
  - Velocity field structure of the filaments and their surroundings

• The observed properties set strong constraints on theoretical models

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→ Linking the large scale magnetic field structure (*Planck*) with the small scale structure (ground based single-dish telescopes and interferometers)

New polarization observations:
- **Single-dish**: 30m/NIKA2-pol, JCMT/SCUBA2/POL2 (e.g., BISTRO)
- **Interferometers**: SMA, ALMA, NOEMA
- **Future space mission(?)**: SPICA/SAFARI/POL

→ Systematic analysis of the velocity field and magnetic field structures

→ Comparing with numerical simulations of molecular cloud formation and evolution

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