Filamentary Structures and Compact Objects in the Aquila and Polaris Clouds Observed by Herschel
Herschel Science Demonstration

- Part of the large Gould Belt KP survey of the nearby star-forming regions
  - More results in talks by Philippe André, Vera Könyves, Sylvain Bontemps

- Aquila Rift and Polaris Flare fields ($D \sim 260$ pc and $\sim 150$ pc)
  - Cores in active star-forming region vs. high-latitude cirrus clouds
  - SPIRE/PACS parallel mode at 70, 160, 250, 350, 500 $\mu$m
  - Angular resolutions of $\sim 8$, 13, 18, 25, 37 arcsec
  - Fields $\sim 3 \times 3^\circ$, cross-scans at 60$''$/s
Herschel Images of the Aquila and Polaris Fields
Aquila and Polaris: PACS 70 µm
resolution ~8”
Aquila and Polaris: PACS 160 µm resolution ~13”
Aquila and Polaris: SPIRE 250 µm resolution ~18"

3.3° 3.3°
Aquila and Polaris: SPIRE 350 µm
resolution ~25”
Aquila and Polaris: SPIRE 500 μm resolution ~37’’
Aquila and Polaris: SPIRE/PACS
RGB 350+160+70 µm and 350+250+160 µm
Aquila and Polaris: SPIRE/PACS
RGB 350+160+70 µm and 350+250+160 µm

- W40
- MWC 297
- Sh 2-62
- Polaris
Aquila and Polaris: SPIRE/PACS
RGB $350 + 160 + 70 \mu m$ and $350 + 250 + 160 \mu m$
Extracting Sources
Multi-Scale, Multi-Wavelength Extraction

- **New method and code** *getsources* developed and used at CEA Saclay
  - No *multi-wavelength* extraction techniques existed for our *Herschel* projects
  - Must use higher resolution or sensitivity information across wavelengths

- Extensively verified at each step of its development
  - Multiple test images, simulated star-forming regions for *Herschel*
  - Star-forming regions NGC 2264, NGC 2068, W 43, Cyg X

- Benchmarked for the Gould Belt consortium, along with several other algorithms using simulated skies of various degree of complexity
  - *gaussclumps* (Stutzki & Guesten 1990)
  - *sextractor* (Bertin & Arnouts 1996)
  - *derivatives* (Molinari et al. 2010)
  - *reinhold* (CUPID software)
  - *clumpfind* (Williams et al. 1994)
  - *mre-gcl* (Motte et al. 2007)
  - *csar* (J. Kirk, private comm.)
  - *fellwalker* (CUPID software)
Benchmark 1: Simple Images
139 objects at 250 μm: effects of S/N, sizes, and separation

S/N = 5  1.0°

S/N = 20  1.0°
Benchmarks 2 and 3: All *Herschel* Bands

350 cores and 100 protostars, shown at 350 µm

background: Bate, Bonnell, & Bromm (2003)
Outline of the *getsources* Algorithm

- **Cleaning**: original observed images at each wavelength $\lambda$
  - Create a set of filtered “*single scales*” separated by a factor of $\sim 1.05$
    
    *successive unsharp masking*: $I_j(\lambda) = G_{j-1} \ast I(\lambda) - G_j \ast I(\lambda)$, $j=1, 2, \ldots, N$
  - Clean each of those scales of noise/background by iterating to $5 \sigma_\lambda$ cut-offs
  - Re-normalize clean scales, sum up over all $\lambda$ into combined detection images

- **Detection**: combined single-scale detection images, independent of $\lambda$
  - Track objects’ appearance, “evolution”, and disappearance: small to large scales
  - Find objects’ positions, S/N, characteristic scales, and footprints

- **Measurements**: original observed images at each $\lambda$
  - Subtract background under the footprints and deblend overlapping objects
  - Measure their fluxes, sizes, and intensity profiles at each wavelength
Aquila and Polaris: SPIRE at 250 µm
single scale ~10”
Aquila and Polaris: SPIRE at 250 μm
single scale ~20"

3.3°

3.3°
Aquila and Polaris: SPIRE at 250 μm
single scale ~40”
Aquila and Polaris: SPIRE at 250 µm
single scale ~80”
Aquila and Polaris: SPIRE at 250 µm
single scale ~160"
Aquila and Polaris: SPIRE at 250 μm
single scale ~320”
Example of Test “Filaments”: Cylinder

getsources does not break uniform filaments
Example of Test “Filaments”: Lena

getsources finds significant peaks that are present
Extracting Filaments
Morphological Component Analysis

- The MCA method and code `cb_mca` developed by J.-L. Starck et al. (2004)
  - Decompose a signal into its morphological building blocks represented by the isotropic wavelets, ridgelets, or curvelets
- Applied the method to analyze large, complex *Herschel* images
  - Separate filamentary structures from the more isotropic structures
  - Decompose images alternating between the curvelet and wavelet transforms
  - Iterate until convergence in both wavelet and curvelet representations
Aquila and Polaris Sub-Fields 1: PACS 70 µm
curvelet components by cb_mca
Aquila and Polaris Sub-Fields 1: PACS 160 µm curvelet components by cb_mca
Aquila and Polaris Sub-Fields 1: SPIRE 250 µm
curvelet components by cb_mca
Aquila and Polaris Sub-Fields 1: SPIRE 350 µm curvelet components by cb_mca
Aquila and Polaris Sub-Fields 1: SPIRE 500 μm curvelet components by cb_mca
Filamentary Structures at All Herschel Wavelengths
Aquila and Polaris: PACS 70 µm
single scales ~40” by getsources
Aquila and Polaris: PACS 160 µm
single scales ~40” by getsources
Aquila and Polaris: SPIRE 350 μm
single scales ~40” by getsources
Aquila and Polaris: SPIRE 500 µm single scales ~40” by getsources
Herschel SPIRE/PACS and Planck 350 μm
angular resolutions ~30” and 300”

Images: ESA, SPIRE, PACS, HFI Consortia, Gould Belt Key Project; http://www.esa.int/esa-mmg
Intimate Physical Relationship of the Filaments and Cores
Aquila and Polaris Sub-Fields 1: SPIRE/PACS
RGB 350+160+70 µm and 350+250+160 µm
Aquila and Polaris Sub-Fields 1: SPIRE/PACS

column densities $N(\text{H}_2)$

<1.4x10^{23} \quad 1.2^\circ \quad <9x10^{21}
Aquila and Polaris Sub-Fields 1: SPIRE/PACS

column densities $N(H_2)$
Aquila and Polaris Sub-Fields 1: SPIRE/PACS column densities $N(\text{H}_2)$

$<1.4 \times 10^{23}$  
$1.2^\circ$

$<9 \times 10^{21}$  
$1.2^\circ$
Aquila and Polaris Sub-Fields 1: SPIRE
single scales ~40": high-contrast filaments and objects
Aquila and Polaris Sub-Fields 1: SPIRE
single scales ~40” + naive visual detection

451 objects 1.2°
168 objects 1.2°
Aquila and Polaris Sub-Fields 1: SPIRE
single scales ~40” + starless cores by getsources

~400 cores  1.2°  ~160 cores
Aquila and Polaris Sub-Fields 1: SPIRE 350 µm
curvelet component by \textit{cb\_mca} + starless cores by \textit{getsources}

\begin{tabular}{|c|c|}
\hline
\textbf{~400 cores} & \textbf{1.2°} \\
\hline
\textbf{~160 cores} & \textbf{1.2°} \\
\hline
\end{tabular}
Aquila and Polaris Sub-Fields 2: SPIRE/PACS
RGB 350+160+70 μm and 350+250+160 μm
Aquila and Polaris Sub-Fields 2: SPIRE
single scales ~40": high-contrast filaments and objects
Aquila and Polaris Sub-Fields 2: SPIRE
single scales ~40” + naive visual detection

105 objects  1.2°

47 objects  1.2°
Aquila and Polaris Sub-Fields 2: SPIRE

single scales ~40” + starless cores by *getsources*

54 cores 1.2°

17 cores 1.2°
Aquila and Polaris Sub-Fields 3: SPIRE/PACS
RGB 350+160+70 µm and 350+250+160 µm
Aquila and Polaris Sub-Fields 3: SPIRE

single scales ~40": high-contrast filaments and objects
Aquila and Polaris Sub-Fields 3: SPIRE
single scales ~40” + naive visual detection

65 objects  1.2°  66 objects  1.2°
Aquila and Polaris Sub-Fields 3: SPIRE
single scales ~40" + starless cores by getsources

34 cores 1.2°
50 cores 1.2°
Two Methods, Same Structures

column density, curvelet component, and single scale

curvelet log-scaled  column density  curvelet  single scale ~40"
Filaments’ Properties and Existing Models
Basic Properties of the Filaments

- Several well-behaved filaments in column density images, original images

<table>
<thead>
<tr>
<th>Field</th>
<th>Column H₂</th>
<th>Temper</th>
<th>&lt;FWHM&gt; deconv</th>
<th>Maximum length</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquila</td>
<td>&lt; 1.4×10^{23}</td>
<td>7.5-15 K</td>
<td>35”±12 ~9000 AU</td>
<td>~0.5 deg ~few pc</td>
<td>$\rho \sim r^{-1.5}$</td>
</tr>
<tr>
<td>Polaris</td>
<td>&lt; 9×10^{21}</td>
<td>10-15 K</td>
<td>60”±12 ~9000 AU</td>
<td>~0.5 deg ~few pc</td>
<td>$\rho \sim r^{-2}$</td>
</tr>
</tbody>
</table>

- Maps of the filaments’ mass per unit length (talk by Ph. André): many Aquila filaments are gravitationally unstable, Polaris filaments are stable
Formation of Filaments and Cores
a few selected models

- MHD simulations of supersonic turbulent motions in weakly magnetized clouds (Padoan et al. 2001): complex system of shocks creating high-density sheets, filaments, and cores
- MHD simulations of turbulent, more strongly magnetized molecular clouds with ambipolar diffusion (Nakamura & Li 2008): sheets, filaments, and cores
- Observed profiles $\rho \sim r^{-1.5}$ and $\rho \sim r^{-2}$ are inconsistent with those of non-magnetic models of hydrostatic filaments, $\rho \sim r^{-4}$ (Ostriker 1964)
- Models of filaments with primarily toroidal or helical magnetic fields can account for profiles $\rho \sim r^{-1}$ to $\rho \sim r^{-2}$, in agreement with observations (Fiege & Pudritz 2000)
Turbulent Fragmentation, Padoan et al. (2001)
slices of the 3D density and velocity fields, Mach ~10
Turbulent Fragmentation, Padoan et al. (2001)
structural resemblance to the observed filaments

column density

Aquila in SPIRE bands, single scale ~40”
Turbulent Fragmentation, Padoan et al. (2001)
structural resemblance to the observed filaments

column density

Aquila at 350 μm, curvelet component
Conclusions

• Fascinating filamentary structures are *everywhere* – as deep as we can see with the sensitivity of our instruments

• All extracted objects (starless cores, prestellar cores, embedded protostars) are *physically* related to the filaments

• The observations suggest that, in general, prestellar cores *originate* in the fragmentation of complex filamentary networks

• To unravel the roles and relative importance of gravity, turbulence, and magnetic fields, we need to obtain additional *kinematic* information
Aquila: Profiles of Selected Objects
azimuthally-averaged intensities

Intensity Profiles of Object 671

Intensity Profiles of Object 689
Aquila: Profiles of Selected Objects
azimuthally-averaged intensities

Intensity Profiles of Object 1050

Intensity Profiles of Object 1077
Aquila: Profiles of Selected Objects
azimuthally-averaged intensities

Intensity Profiles of Object 1213

Intensity Profiles of Object 1570
Aquila: Profiles of Selected Objects

azimuthally-averaged intensities

Intensity Profiles of Object 1587

Intensity Profiles of Object 2084