Cold Cores of Molecular Clouds

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On behalf of the Planck and Herschel projects on cold cores
Content

- Molecular clouds and star formation

- Cold Cores
  - Observations and interpretation
  - Project Galactic Cold Cores → Planck & Herschel

- Some notes on modelling – moderating the interpretation of observations
The Milky Way - in dust emission

Galactic disc
~30 kpc

Star forming cloud
~10^{1-2} pc  ~10^{0-5} M_\odot

Clumps, cores
~0.1-1 pc  ~0.1-10 M_\odot

Planck – ESA and the HFI Consortium
Galactic Cold Cores & dust

- Far-infrared and sub-millimetre dust emission probes dense molecular clouds, especially the **cold** phase
- A tracer of the **pre-stellar phase**
  - The initial conditions for the birth of **stars** and **planetary** systems
  - The **density** and the **temperature**
    - ... only estimates of the **column density** and **colour temperature**
- How does dust itself evolve?
  - $\kappa$ and $\beta$ change because of grain growth, ice mantles... probably also as function of $\nu$ and $T$
The objects

- **Cold** cloud cores, where the stars are born
  - $T$ down to 6K? (Evans et al. 2001, Galli et al. 2002; Pagani et al. 2003; Crapsi et al. 2007; Harju et al. 2008)
- We want to **understand** the physics
  - Density → the origin of the density field
  - Temperature → factors affecting thermal balance
  - Velocity field → core formation and evolution

The tools

- Observations of **spectral lines**
- Observations of **dust**
  - thermal dust emission
  - light scattered by dust
  - light extinction
• **Space-borne far-infrared** surveys: Estimates of $T_{\text{dust}}$, not very sensitive to cold dust (IRAS, ISO, AKARI, Spitzer)

• **Ground based (sub-)mm** observations: Often no $T_{\text{dust}}$ data, better resolution (Scuba, LABOCA, Bolocam, MAMBO)

• **Balloon-borne (sub-mm)** observations: Large area, multi-wavelength surveys (PRONAOS, Archeops, BLAST, etc.)

• **Space-borne sub-millimetre and radio** observations: Several frequencies, large areas, high sensitivity → *Planck*, Herschel
Cold Cores & Planck

The Planck satellite mapped the sky at nine sub-millimetre and radio wavelengths

- 350µm, 550µm, 850µm, ..., 1cm
- better than 5' resolution in the sub-mm

This enables the detection of cold clumps!

Planck is also the first mission capable of a full survey

- full sky coverage
- sub-millimetre bands
- sufficient resolution
- excellent sensitivity
Preliminary catalog contained over 10000 sources, some 900 of which were included in the Early Cold Clumps catalogue (Planck collaboration 2011)

- distances from 100pc to 8kpc, Galactic heights up to ± 400pc
Cold Cores & Herschel

Key Programme **Galactic Cold Cores**

- to map ~120 fields containing cold Planck clumps
- a **cross-section** of the full population (T, M, n, R, l, b etc.)

- complementary to other programmes → includes high latitudes, outer regions of molecular cloud complexes, large distances

  - cf. **Gould Belt Survey** (Andre), **HIGAL** (Molinari), **EPOS** (Krause), and many other key programmes and normal programmes
Distribution of the ~120 Herschel target fields that include over 350 Planck-detected cold clumps
Morphology

- Isolated, cometary, filamentary, etc.
- Occasionally indications of dynamic interaction
- Further quantitative analysis
  - Clump mass spectra, P(D) analysis, filament extraction
Star formation

- WISE data show that a many cold sub-millimetre clumps are already associated with star formation.
CMF – Clump/core mass function (work in progress)

- can CMF be described with a unique power-law; what is the connection with the IMF
  - Motte et al. (1998)... Könyves et al. (2010) – talk by Ph. Andre
- in case of GCC, no more than ~100 c's per field → distance scatter make a joint study more challenging
- another goal: correlation of clumps and YSOs
  - J. Montillaud (in preparation)
- eventually: the internal structure of individual cores
  - \( n, T \) – requires radiative transfer modelling of the data
  - e.g., Sadavoy et al. 2012; Nielbock et al. (?) B68 etc.
P($A_v$) analysis

- tail above the log-normal distribution is related to star formation? (Kainulainen et al. 2009, 2011)
- the analysis can be done now using Herschel column densities
**Dust physics**

Coreshine?

- In dense cloud cores **scattered light** has been detected as surprisingly long wavelengths
  - \(~3.5\mu m\) signal caused by the growth of dust particles? (Steinacker et al. 2010, Pagani et al. 2010)
- In WISE data of 56 fields, four detections, six tentative det.
  - there is a follow-up Spitzer programme on 90 Planck clumps, PI **R. Paladini**
\( \beta(T) \) relation?

- The spectral index \( \beta \) **appears** to decrease with temperature, as suggested by laboratory data.... but
  - also **the noise** can produce an apparent anticorrelation
  - **temperature variations** decrease the apparent \( \beta \)

\[ \rightarrow \] need Monte Carlo and/or (hierarchical) statistical modelling to find the (~) un-biased truth

- Planck Early Results XXIII; Kelly et al. 2012; Veneziani et al. 2012 (submitted); Juvela et al. (in prep.)
Molecular lines

- Velocity-resolved line data **essential**
  - kinematic distances, separation of kinematic components, estimates of turbulent support
- internal kinematics
  - rotation, infall, outflows
- main gas parameters
  - density, temperature
- chemistry
  - age, deuteration, depletion
- Observations ongoing
  - APEX, Onsala 20m, IRAM 30m, Effelsberg, CSO; see also Wu et al. (2012), Liu et al. (2012)
Modelling

- to **understand** the limitations of the observations
  - to show uncertainties and biases, still usually under idealised conditions
- to **extract** the most information from the data
  - e.g., to estimate the temperature and density structure of a core when only projected surface brightness data are available; to separate dust properties from radiation field effects etc.
\( \beta (T) \) relation

- We know the observed spectral index is affected by
  - observational noise → artificial \((\beta, T)\) anticorrelation
    - Shetty et al. (2009b); Juvela & Ysard (2012b); Kelly et al. (2012); Veneziani et al. (2012)
  - mixing of temperatures → lower apparent \(\beta\) values
    - Shetty et al. (2009a); Juvela & Ysard (2012a)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{beta_vs_temperature.png}
\caption{(2012b) Noise can be strongly non-gaussian}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{correlation.png}
\caption{(2012a) Positive or negative correlation - depending on the set of sources}
\end{figure}
The difference between cores that are heated externally by ISRF or by embedded protostars?

High resolution AMR MHD + radiative transfer modelling (see Lunttila et al. 2012)

Positive correlation!
Filaments

- Can we measure the filament profiles?
  - Up to a point. With Herschel the limit is at a few 100 pc
- Are some 'filaments' formed by a chance alignment
  - Possibly. This should apply more to clumps/cores (CMS!)

\[
\rho_p(r) = \frac{\rho_c}{\left[1 + \frac{(r/R_{\text{flat}})^2}{|p/2|}\right]}
\]
For nearby filaments, even 2MASS stellar colour excesses are enough to constrain filament properties

- ... the average profile

Malinen et al. (2012)
Summary

- **Sub-millimetre** observations **locate** pre-stellar clumps
  - The **Planck** survey is resulting in a catalogue of more than 10,000 cold clumps in the Milky Way
- High resolution data from the **Herschel** satellite reveal the **structure** of the clumps and their environment
  - Often fragmented, many already containing young stars
- Data must be complemented with **other wavelengths**
  - mid-infrared to trace young stellar objects, molecular lines to measure gas temperature and to map cloud kinematics
- Numerical **modelling** help us to understand what we see
  - … or reveals things we cannot see or do not yet understand
- The first summary of the Herschel project **Galactic Cold Cores** is to be expected within a year
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