The dynamic interstellar medium as a tracer of galactic evolution

1. Science aim: Understand molecular cloud formation and feedback from star formation through gas kinematics in the different phases of the filamentary ISM

2. (i) Scientific Importance:

Herschel images of dense interstellar clouds (e.g., André et al. 2010; Molinari et al. 2010) have revealed spectacular networks of filamentary structures with chains of embedded cold cores where stars are born (see Fig. 1). The ubiquity of filamentary structure shown by the *Herschel* observations, together with the concentration of dense cloud cores and young stars along the filaments, has provided the impetus for the recognition that *understanding star formation means understanding filamentary structure in molecular clouds*.

Observational results point to a paradigm in which interstellar filaments and dense prestellar cores arise from different phases in the star-formation process: first, large-scale supersonic flows compress the gas into sheets which fragment to form filamentary structures; then gravity takes over, causing subsequent breakup into cores. The observed column density threshold (or maximum stable mass per unit length) for star formation in filaments corresponds theoretically to the threshold above which filaments are gravitationally unstable, thus prone to core formation (e.g., Onishi et al. 1998; Arzoumanian et al. 2013; André et al. 2014). It is thought, though not yet certain, that beyond the Milky Way, star formation processes may be intimately connected with filaments, "spurs", and "feathers" in spiral galaxies (e.g., Smith et al. 2014, see Fig. 1). Moreover, gravitational instabilities are also at work in external galaxies, prompting the idea that filaments may regulate star formation efficiency in dense molecular gas, and may be ultimately responsible for the quasi-universal star-formation law in the dense ISM of galaxies (e.g., Lada et al. 2012).

Filaments vary in length (40-100 pc), but are rather uniformly narrow, ~0.1-0.2 pc in width. (Self-gravitating) filaments probably acquire mass through accretion of background material, with typical infall rates of 0.5-1 km/s. The universality of the narrow ~0.1 pc width of filaments is almost certainly a signature of the same underlying physics driving structure formation. Various theories suggest that gravity, turbulence, magnetic fields, and jet/outflow stellar feedback all play a role in filament formation and evolution (e.g., Federrath 2016). Once stars have formed in the dense cores, massive stellar winds and eventually supernovae explosions further shape the ISM through shocks and turbulence (see Fig. 1). Models predict that velocity dispersion is subsonic within the filaments and supersonic outside; the only way to test this and similar predictions is with detailed **kinematics**. Spectrally-resolved observations of the different ISM phases (molecular, atomic, and ionized) are needed to disentangle the physical processes behind filamentary structure formation, the formation and evolution of dense cores, and their conversion into stars. *Mapping the kinematics of the different ISM phases within filaments in the Milky Way and in a wide variety of nearby galaxies in the Local Universe will open a new discovery window on the role of filaments for star formation, ultimately relating the small-scale star-formation processes and the ISM energy cycle within galaxies to their evolution*.

(ii) Measurements Required:

Velocity- and spatially-resolved maps in the Galaxy and in external galaxies are needed to disentangle the contributions of the various ISM phases along the line of sight in filaments, in terms of the dense, star-forming molecular gas, photon-dominated cloud interfaces, the diffuse molecular and atomic material, and ionized gas. Velocity resolution is particularly important for mapping filaments at extragalactic distances where it is virtually impossible to spatially resolve them along the narrow direction. The composition of gas and dust in filaments is so far relatively unknown, although recent simulations suggest that filamentary molecular clouds may be part of much larger structures better probed by tracers other than CO. Extinction varies along filaments, and different tracers are needed in these regions.

What lines and what spectral resolution do we need? We need to measure the kinematics of the atomic, molecular, and the ionized phases of the ISM. FIR fine-structure (FS) lines trace *ionized gas* ([NII] 122, 205µm; [OIII] 52µm, 88µm), and atomic carbon (e.g., [CI] 370µm) probes the *atomic component* associated with diffuse, translucent molecular gas. The high-J CO transitions in the FIR probe *molecular gas*, and are useful for tracing the energy released in filament formation (e.g., slow shocks)[1]. Water lines (e.g., o-H_2O 1_{10}-1_{01} 538µm, o-H_2O 2_{12}-1_{01} 180µm) are also powerful probes of shocks. The major ISM coolants are also found in the FIR regime ([CII] 158µm; [OI] 63µm, 145µm). [CII] is usually the brightest cooling line, and together with [CI], prominent in regions of low extinction and an effective tracer of CO-dark molecular gas, which would otherwise be difficult to assess in metal-poor environments. [CII] emission is linked to star-formation rate (SFR), and arises mainly from dense, warm, photon-dominated regions (PDRs), but also from ionized and atomic gas, making the availability of other FIR FS lines crucial to its interpretation. *Due to the very modest gravitation of the filamentary structures, the accretion velocities will be only a fraction of a km/s.* The high angular resolution of OST combined with a spectral resolution 1.5×10^6 (0.2 km/s) of a heterodyne instrument operating at 1900 GHz are both required to probe this critical step taking filaments to cores and thus to stars. Such a resolution is also necessary to assess the physical conditions probed by the different tracers and velocity components of the gas. More details are given in the Appendix.

(iii) Uniqueness to 10µm to few mm wavelength facility:

In the Milky Way and nearby galaxies in the Local Universe, these FIR transitions are impossible to measure from the ground. Low-J CO lines are available from the ground, but do not trace the material in transition between atomic and molecular phases. Studying and interpreting ISM cooling and kinematics in filaments is possible only from space with an FIR facility.

(iv) Longevity/Durability: (with respect to expected 2025-2030 facilities)

JWST, ALMA, WFIRST, SOFIA, EELT, etc.

The transitions discussed above are observable with ALMA only at high redshifts, so this program is complementary and necessary for a reliable local benchmark ranging from Milky Way spatial scales to external galaxies. JWST does not cover the appropriate wavelength range, and SOFIA is not able to reach the low column density regions where the formation of filaments is initiated.

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[1] Physical conditions in the gas -metallicity, excitation, and density- may affect the viability of high-J CO as a reliable tracer of H_2.

Bibliography

André, Ph., et al. 2010, A&A, 518, 102
André, Ph., et al. 2014, Protostars and Planets VI, p. 27-51
Arzoumanian, D., et al. 2013, A&A, 553, 119
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Lada, C. J., et al. 2012, ApJ, 745, 190
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Onishi, T., et al. 1998, ApJ, 502, 296
Smith, R. J., et al. 2014, MNRAS, 441, 1628

3. Figure:

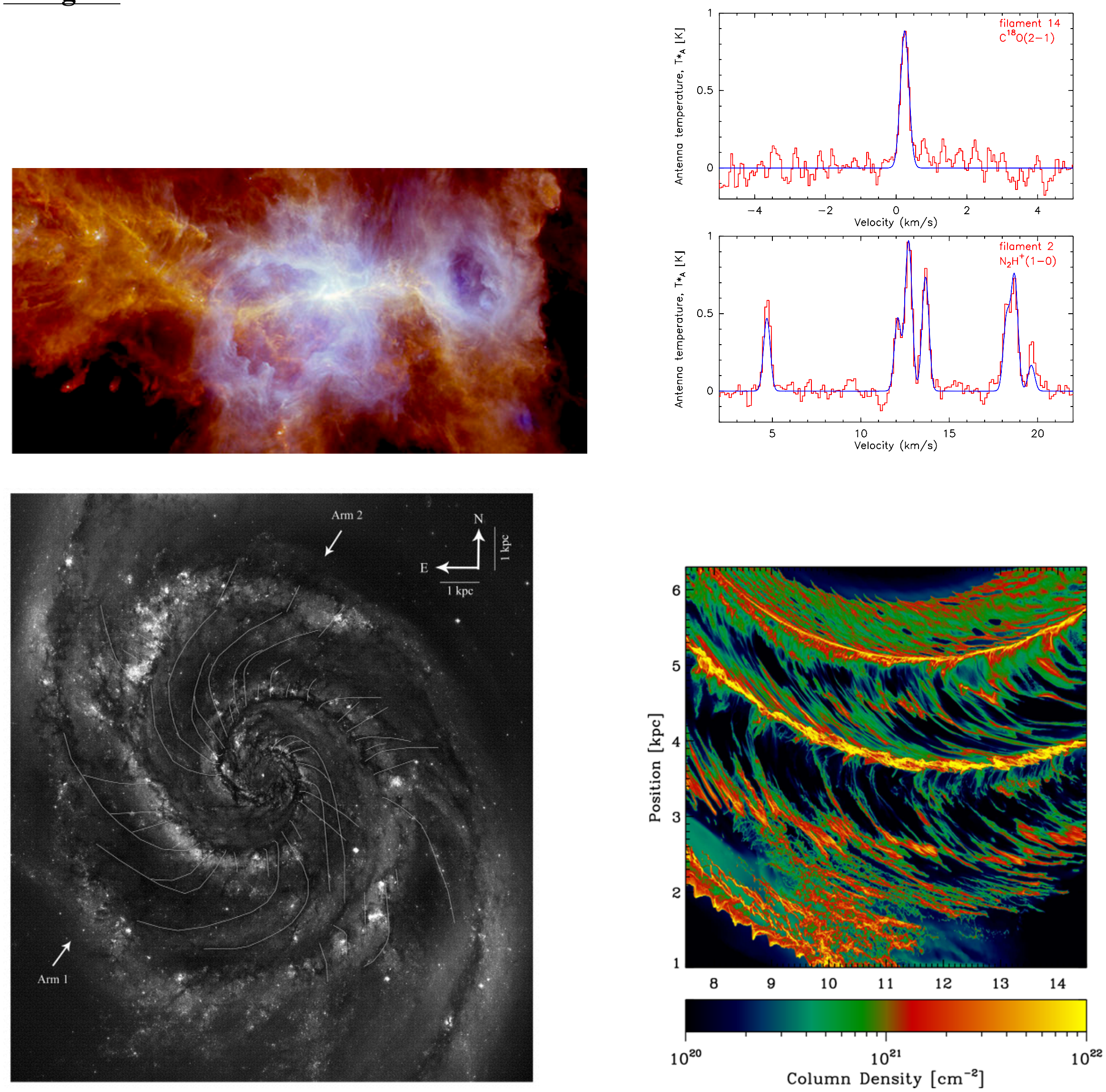

Figure 1. Upper left panel: Filamentary network in the Orion A molecular cloud (ESA/Herschel André et al 2010, for the Gould Belt survey Key Programme); upper right: observed spectra in the $C^{18}O$(2-1) and N^2H^+(1-0) transitions in IC 5146 (Arzoumanian et al. 2013); lower left: M51a with HST showing the feathers/filaments connecting the spiral arms as light curves (La Vigne et al. 2006); lower right: models of feathers/filaments (without magnetic fields) by Smith et al. (2014).

4. Performance Table:

Parameter	Unit	Required value	Desired Value	Comments
Name of line(s)	[OI], [CII], [OIII], [NII], [CI], CO, o-H_2O 1_{10}-1_{01} (538μm), o-H_2O 2_{12}-1_{01} (180μm)			
Wavelength/band	μm/ *GHz*	50-550 μm	50-550 μm	> 500 μm is required for an important water line, o-H_2O 1_{10}-1_{01} (538μm)
Number of targets		50-100	300-500	
Survey area	$deg.^2$			
Angular resolution	arcsec	2"-5"	1"-2"	to resolve the longitudinal filament dimension at 5-10 Mpc distances in external galaxies
Spectral resolution	Δλ/λ or km/s	<= 0.5 km/s (R ~ 10^6)		
Full Line Bandwidth	*km/s*	300 km/s	500 km/s	not line width (expected to be narrow), but need to span the possible rotation velocities in external galaxies, even if minimized in low-inclination systems
Continuum Sensitivity (1 σ)	μJy	NA	NA	--
Spectral line sensitivity (1 σ)	W m-2 *K*	~10^{-21} Wm^{-2}	10^{-22} Wm^{-2}	to detect [NII] 122 μm in external galaxies; [CII] 158 μm expected to be 10 times brighter
Signal –to-noise		5		
Dynamic range		> 100		
Heterodyne Rx	***specific***	***questions:***		
Required Tuning range (Dopplershift)	*km/s*	-300 km/s- 1000 km/s		to accommodate the recession velocities in external galaxies
Polarization measurements required?	*NO*			
Off position requirements: Fixed throw, or dedicated off?	*5-30 arcmin*			dedicated off throw amplitude depends on the sizes of the external galaxy and of the Galactic star-forming regions

5. Key references:

André, Ph. et al. 2014, Protostars and Planets VI, p. 27-51: *From Filamentary Networks to Dense Cores in Molecular Clouds: Toward a New Paradigm for Star Formation*

Federrath, C. 2016, MNRAS, 457, 375: *On the universality of interstellar filaments: theory meets simulations and observations*

Smith, R. J. et al. 2014, MNRAS, 441, 1628: *CO-dark gas and molecular filaments in Milky Way-type galaxies*

6. Overall topics (OST science themes)

- Revealing the Interplay between Stars, Black Holes, and Interstellar Matter over Cosmic Time
- Charting the Rise of Metals, Dust, and the First Galaxies

7. Appendix: Observational requirements in more detail

Filaments are extended structures, but contain small-scale structure that must be spatially resolved (in the Milky Way) in order to understand their structure and evolution. Representative values of the size of region that must be imaged to discern the structure and gas kinematics is 0.5 pc, while the size of the small-scale sub-filaments is approximately 0.004 pc. Thus, an image with a spatial dynamic range ~125 is required, which contains $\sim 2\text{x}10^4$ pixels. This is not simply to have a 'pretty picture' but to be able to understand the dominant physical properties that govern the evolution and fragmentation of filaments, and thus determine the star formation that will take place within them.

To map the different ISM phases and kinematics in filaments of nearby galaxies, we need [CII] 158µm; [OI] 63µm, 145µm; [NII] 122, 205µm; [OIII] 52µm, 88µm; and [CI] 370µm. High-J CO transitions fall within these wavelength ranges (e.g., ^{12}CO(30-29) 87.2µm, ^{12}CO(10-9) 260µm). Measurements of the *faintest* local dwarf galaxies (IR luminosity, LIR ~ 10^7 $L_\odot$) suggest that detection of [NII] 122 µm, the *faintest* FIR FS line (typically 10 times fainter than [CII]), requires a 5σ sensitivity at z~0 of $\approx 2\text{x}10^{-10}$ Wm^{-2} sr^{-1}, or considering a beam of 1 square arcsec, $\approx 5\text{x}10^{-21}$ Wm^{-2}.

Adopting a SSB system noise temperature of 2000 K, a velocity resolution of 0.2 km/s, and required rms antenna temperature of 0.1 K yields 315 s observing time per image pixel (ignoring overhead and reference position noise). The total time required to obtain the image is 2070 hr/N_{el}, where N_{el} is the number of elements in the heterodyne receiver focal plane array. To carry out this project in a reasonable amount of time requires a large focal plane array. With N_{el} = 64, 32 hours for each source is required (still neglecting overhead, reference observations, and calibration time). This time request is, however, sufficiently modest that a sample of filaments in different clouds of different types at different distances, and in selected nearby galaxies, can be studied as part of a single Key Project. A 128-element array would speed things up another factor of two, and would thus allow a greater range of sources to be observed.

A possible strategy for external galaxies would be pointed observations at relatively face-on objects from the Local Volume Legacy (LVL) survey, with previous IR detections in order to optimize detectability of the FIR lines. Additional galaxies could be added, within some distance threshold, in order to maximize the span of SFR, stellar mass, and metallicity. We find > 100 galaxies within ~10 Mpc, inclinations < 60^{o} , previous IR detections, and sufficiently large to map. Mapping such a sample spanning a wide parameter space would provide an indispensable local benchmark for high-z studies in similar tracers.

This case has some elements in common with Science case #22: Star Formation and Multiphase ISM at Peak of Cosmic Star Formation and with Science Case #7: Magnetic fields and turbulence – role in star formation. This case also has something in common with Science Case #2 (Regulating the multiphase ISM) which however requires H_2 rotational lines (17, 28 µm) and no [CI] 370 µm or high-J CO.

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