Origins: From the Protosun to the First Steps of Life
Proceedings IAU Symposium No. 345, 2018
B. G. Elmegreen, L. Viktor Tóth & M. Güdel, eds.

doi:10.1017/S1743921319002102

ALMA observations of the Orion Integral Filament: evidence for fibers in a massive cloud

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Abstract. The connection between low- and high-mass filaments is a matter of strong debate. In order to bridge these two filamentary regimes, we have investigated the internal structure of the Integral Filament in Orion using ALMA observations of the N_2H^+ (1-0) emission line in Band 3 in combination with previous single-dish data. Our ALMA mosaics, the largest of its kind carried out so-far in local clouds, reveal the presence of multiple sonic-like fibers inside this massive filament. In combination with the identification of fibers in regions such as Taurus, Musca, and Perseus, the first unambiguous detection of fibers in Orion highlights the importance of these gas substructures as the fundamental building blocks of both low- and high-mass filaments.

Keywords. stars: formation, ISM: kinematics and dynamics, ISM: clouds, radio lines: ISM

1. Fibers in low-mass filaments

The unprecedented sensitivity of the Herschel observations has revealed the presence of filaments in low- and high-mass star-forming regions, harbouring most of the cores and stars formed within molecular clouds (see André *et al.* 2014, for a review). The ubiquitous detection of filaments highlights the key role of these gas structures determining the initial conditions for star-formation. However, the detailed origin of stars in both low- and high-mass filaments remains poorly understood.

Recent molecular observations have investigated the internal substructure of several Herschel filaments with exquisite detail. From the analysis of different millimeter line tracers, Hacar *et al.* (2013) demonstrated that the previously described as single B213-L1495 filament in Taurus, is actually a collection of small-scale elongated substructure, referred to as *fibers*. These fibers are characterized by a quiescent velocity structure, showing sonic-like internal motions. They contain all the dense cores within this region, passing on their quiescent properties to these stellar seeds. After their original discovery, fibers have been systematically detected in low-mass star-forming regions such as Musca (Hacar *et al.* 2016) and Perseus (Hacar *et al.* 2017a). Hydrodynamical simulations (e.g., Smith *et al.* 2014) suggest these fibers as the first sonic-like structures decoupled from the turbulent cascade, regulating the transition between the supersonic diffuse gas and the quiescent dense cores prior to the formation of stars.

In a recent work (Hacar *et al.* 2018), our group reported the first direct evidence of fibers in the Integral Shape Filament (ISF; see Johnstone & Bally 1999) in the Orion A cloud. The ISF is the most massive filament in the solar neighbourhood (D∼ 414 pc, Menten *et al.* 2007) and the only one forming high-mass stars (aka Trapezium). The ISF is usually regarded as a local benchmark of current star-formation theories. The detection of fibers in this unique target can help to unify our current description of the internal structure of both low- and high-mass filaments.

2. ALMA observations in the ISF

We have investigated the Orion ISF using the Atacama Large Millimeter Array (ALMA). We observed the central spine of the ISF filament covering the Orion Nebula Cluster (ONC), including the Trapezium stars and Orion BN/KL source, and both OMC-1 and OMC-2 clouds (see Fig.1, Left panel). Our observations targeted the N_2H^+ (1-0) line (93.173 GHz, Band 3) and combine two 150-pointing interferometric ALMA-12m mosaics with previous IRAM30m (single-dish) observations (Hacar *et al.* 2017a). The full reduction process and combination of single-dish plus interferometric maps is described in Hacar *et al.* (2018). These data are part of the ORION-4D project and are available on-line in a public website (see `https://sites.google.com/site/orion4dproject/`).

We display the total integrated intensity N_2H^+ (1-0) map of the ISF in Fig. 1 (Central panel). Our observations correspond to the largest ALMA mosaic carried out so-far in local star-formation studies. Our final map is convolved to a final beamsize of 4.5", corresponding to a spatial resolution of $\sim$ 2000 AU at the distance of Orion. Our observations cover a total of 2 orders of magnitude in scale, from the total length of $\sim$ 2 pc of the ISF down to 2000 AU. Moreover, the unique combination with our previous IRAM30m observations allow us to recover all relevant scales.

Our maps show the internal substructure of the ISF with unprecedented detail. As density selective tracer, the N_2H^+ (1-0) emission reveals the internal distribution of dense gas ($>10^5$ cm^{-3}) within this filament. As seen in Fig. 1 (Central panel), the gas in both OMC-1 and OMC-2 regions is strongly organized in multiple elongated gas fibers forming a complex network (see also Sect. 3 for a discussion of their properties). Despite the differences in resolution and sensitivity, the same gas substructure is also observed in the continuum (Fig. 1, Left panel) ruling out contamination, abundance, and/or excitation effects affecting our analysis. The observed ALMA fibers contain most of the dense cores, continuum sources, and protostars identified within the ISF (see also Fig. 1 left panel). For the first time, our new ALMA observations reveal the intrinsic fibrous substructure of the massive Orion ISF.

3. Narrow fibers in Orion

We have characterized the observed ISF substructure using a new hierarchical version of the Friends-In-Velocity algorithm (see Hacar *et al.* 2013), namely, Hi-FIVE (see Hacar *et al.* 2018, for a description). Hi-FIVE simultaneously considers both the spatial and velocity distribution of the cloud in order to extract those velocity-coherent structures found within complex molecular datacubes. From the analysis of our more than 75 000 N_2H^+ (1-0) spectra, Hi-FIVE identifies a total of 55 independent fibers, recovering $\sim 90\%$ of the total emission of this molecule detected within our ALMA maps. We show the spatial distribution of fibers in Fig. 1 (Right panel; red segments). These fibers explain the full internal structure of the ISF forming a complex and intertwined network in both OMC-1 and OMC-2 regions.

Our HiFIVE algorithm allows us to statistically investigate the physical properties of the ISF fibers. In Figure 2, we show the cumulative distributions of all the non-thermal motions in units of the local sound speed (Left panel), the mass-per-unit-length (Central panel), and total length (Right panel) of all detected fibers in both OMC-1 (blue) and OMC-2 (red) regions. We compare these two fiber populations with the

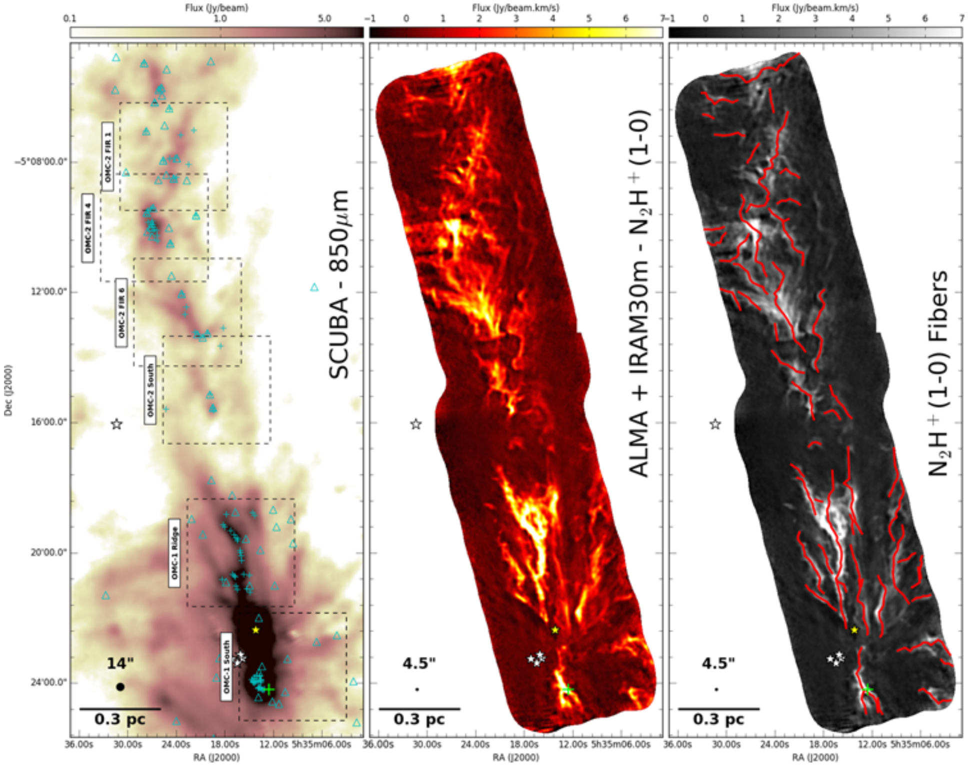

Figure 1. ALMA observations of the Orion ISF (see Hacar *et al.* 2018, for details): (Left) SCUBA-850μm continuum emission (Johnstone & Bally 1999), (Centre) ALMA-12m + IRAM30m N_2H^+ (1-0) integrated emission, and (Right) the 55 velocity-coherent fibers detected in N_2H^+ (main axis indicated by red segments). The location of all the continuum sources (blue crosses) and Spitzer protostars (blue triangles) are indicated in the continuum image. For reference, the position of the Trapezium (four white stars), the Orion BN/KL region (yellow star), and NU Ori star (white isolated star), are indicated in all panels. The synthesized beamsize of our ALMA observations (4.5" or $\sim$ 2000 AU) is indicated in the lower corner of both central & right panels. We note the unprecedented large dynamic range in resolution and sensitivity of our combined ALMA+IRAM30m observations.

observed properties of fibers in clouds such as NGC1333 in Perseus (orange), B213 in Taurus (black), and Musca (green) reported in previous studies. As illustrated by this comparison, fibers show similar properties in terms of internal motions (left panel) and mass distribution close to hydrostatic equilibrium (central panel). Independently of their environment, fibers are recognized as the first sonic structures (i.e., $\sigma_{NT}/c_s \sim 1$) in both low- and high-mass clouds.

While we find similar kinematics, we identify a systematic change in the physical size and width of fibers in regions of increasing mass. In Figure 3, we display two independent fibers observed in the Taurus (left) and Orion (right) clouds, both detected in N_2H^+ (1-0), at the same physical scale. In regions like Taurus, fibers present a typical Full-Width-Half-Maximum (FWHM) of $\sim$ 0.1 pc, consistent with the expected constant filament width observed in Herschel filaments (see Arzoumanian *et al.* 2011). On the contrary, the Orion fibers show much narrower widths on the order of $\lesssim 0.03$ pc. A similar trend is observed in the reported fiber lengths between Taurus ($\sim$ 0.5 pc) and Orion ($\sim$ 0.15 pc) (see Fig. 2, Right panel). While similar in kinematics, our ALMA results indicate a

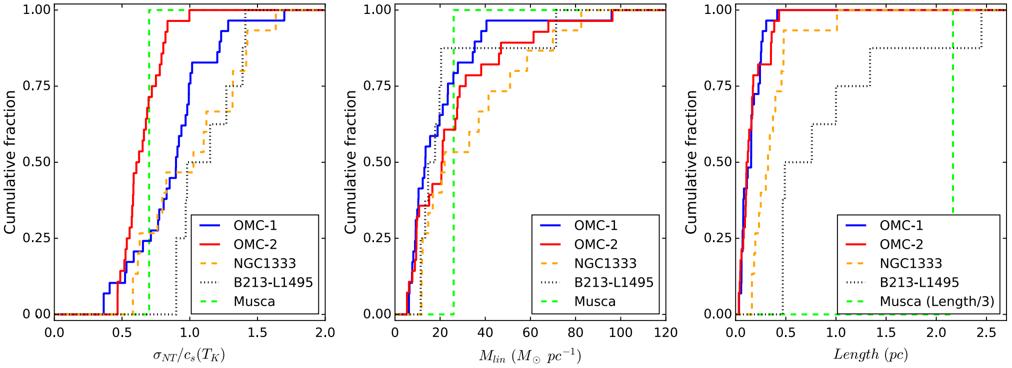

Figure 2. Statistical properties of fibers in the OMC-1 (blue), OMC-2 (red), NGC1333 (orange), B213 (black), and Musca (green) filamentary regions. All panels show the cumulative distribution of (Left) Non-thermal velocity dispersion (σ_{NT}) in units of the local sound speed (c_s), (Centre) mass-per-unit-length (M_{lin}), and (Right) total Length of all fibers detected in these regions.

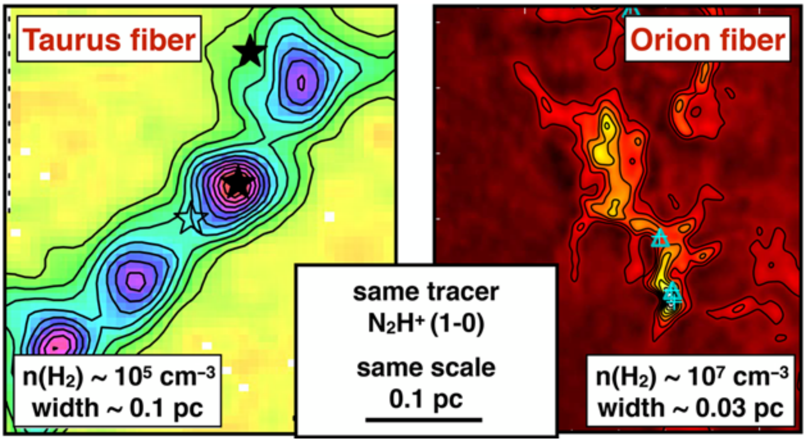

Figure 3. Observed fiber widths in Taurus (Left panel; Tafalla & Hacar 2015) and Orion (Right panel Hacar *et al.* 2018) detected in N_2H^+ (1-0). Both images are displayed at the same physical scale. We note the large differences between the observed fiber widths in these two regions.

systematic change on the physical size and width of fibers between low- and high-mass regions, likely associated with the change in density between these environments.

4. Fibers in low- and high-mass filaments

Originally identified in low-mass filaments like Taurus or Musca, increasing number of studies have suggested the presence of fiber-like structures in regions of increasing complexity such as young proto-clusters (e.g., Fernández-López *et al.* 2014) and Infrared Dark Clouds (e.g., Henshaw *et al.* 2014). Our ALMA results extend the detection of fibers into massive filaments. In particular, the first unambiguous detection of these objects in Orion indicates that fibers are the fundamental building blocks of low- and high-mass filaments. In all environments, fibers regulate the formation of dense cores and stars, playing a pivotal role in the star-formation process. In both low- and high-mass filaments fibers are described by their quiescent internal dynamics and a quasi-stable configuration.

Remarkably, fibers seem to adapt their widths and lengths to the density of their local environment (see Hacar *et al.* 2018, for a full discussion).

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Discussion

LISEAU: The 1-0 transition of N_2H^+ has an upper level energy less than 5K implying that in Orion considerably higher levels will be predominantly populated, making mass determinations based on (1-0) potentials very uncertain. Furthermore, relative intensities of the main and satellite components indicate the levels to be severely optically thick, making them unsuitable for mass determinations.

HACAR: Under normal conditions, the high column densities observed in Orion would indeed lead into highly optically thick lines of $N_2H^+(J=1-0)$. However, much to our surprise, the high-densities ($\sim 10^7$ cm^{-3}) and relatively higher temperatures ($\sim 20-30$ K) found in the dense gas in Orion help to keep this $J=1-0$ transition optically thin. Using RADEX calculations, in our paper (Hacar *et al.* 2018) we demonstrate that this combination of temperature and density excite many molecules at higher J-states ($J >$ 2...3), depopulating the $J=1-0$ level and making this fundamental level optically thin. Our estimates are also in agreement with our direct measurements of the $N_2H^+(1-0)$ lines and their hyperfine structure showing low line opacities.

KHAIBRAKHMANOV: What is the magnetic field direction in the Orion filament and in subfilament structures?

HACAR:The morphology of the B fields changes significantly along the ISF region. In OMC-1, the B-field shows an hourglass shape (see Ward-Thompson *et al.* 2017) likely created by the gravitational collapse of this region (Hacar *et al.* 2017a). In OMC-2, the B-field morphology is less organized and its origin is less clear (e.g., see Matthews *et al.* 2009).

ZINNECKER: Do the fiber bundles oscillate back and forth hydromagnetically, as proposed in the slingshot theory of the integral-shaped filament in Orion?

HACAR: At large scales, our fibers follow a velocity profile created by the gravitational collapse of the OMC-1 reported in our previous study (Hacar *et al.* 2017a). These results contradict the so-called “slingshot mechanism” as they are collapsing motions rather than oscillations or ejections.