From Interstellar Clouds to Star-Forming Galaxies: Universal Processes?
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The role of interstellar filaments in regulating the star formation efficiency and shaping the initial mass function

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Abstract. Recent surveys at infrared and submillimeter wavelengths with the *Spitzer* and *Herschel* space observatories suggest that star formation in dense molecular gas is governed by essentially the same "laws" in nearby Galactic clouds and distant external galaxies. This raises the possibility of a unified picture for star formation in the Universe from individual-cloud scales to galaxy–wide scales. We summarize the star formation scenario favored by *Herschel* studies of the nearest molecular clouds of the Galaxy which point to the key role of the quasi-universal filamentary structure pervading the cold interstellar medium.

Keywords. stars: formation, ISM: clouds, ISM: structure, ISM: individual objects (Aquila Rift complex), submillimeter

1. The filamentary interstellar medium

Interstellar filaments were already seen earlier in molecular clouds (e.g., Schneider & Elmegreen 1979; Hartmann 2002; Myers 2009), after which *Herschel* observations not only confirmed their omnipresence, but the ubiquity of filaments also revolutionised our view of star formation in the Galaxy.

The *Herschel* Gould Belt survey (HGBS, André *et al.* 2010) observations confirm the omnipresence of filaments in nearby molecular clouds and suggested a close connection between the filamentary structure of the cold ISM and the formation process of prestellar cores (André *et al.* 2010, Men'shchikov *et al.* 2010). Besides, other *Herschel* imaging programs such as HOBYS (Motte *et al.* 2010), HiGAL (Molinari *et al.* 2010), and EPoS (Henning *et al.* 2010) demonstrated the presence and importance of filaments in the interstellar medium. These filaments present a high degree of universality, including their typical inner radial width of $\sim$0.1 pc (e.g., Arzoumanian *et al.* 2011, Palmeirim *et al.* 2013, Koch & Rosolowsky 2015), and they likely play a central role in the star formation process (see for a review André *et al.* 2014).

2. Spatial distribution of prestellar cores

One of the main goals of the HGBS is to elucidate the physical mechanisms responsible for the formation and evolution of prestellar cores in molecular clouds. In the Aquila cloud complex based on *Herschel* data† we have identified a complete sample of 651 starless cores extracted with the multi-scale, multi-wavelength source finding algorithm *getsources* (Men'shchikov *et al.* 2012). Approximately 60% $\pm$ 10% of this sample are

† The *Herschel* products of the Aquila molecular cloud, including maps and catalogs, can be found at the *Herschel* Gould Belt Survey Archive, http://gouldbelt-herschel.cea.fr/archives.

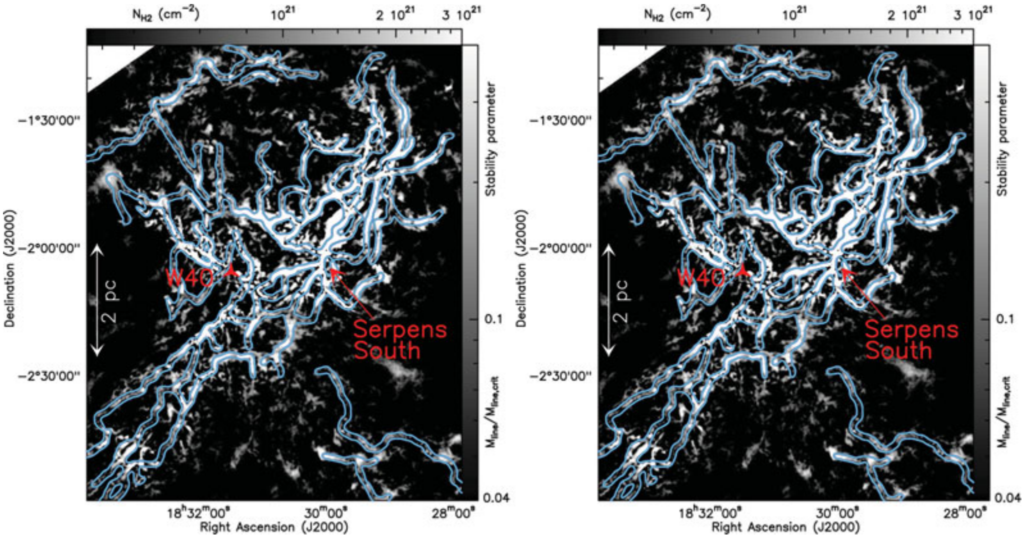

Figure 1. Left: Curvelet component of the *Herschel* column density map of Aquila, showing the main region in equivalent mass per unit length along the filaments (cf. André *et al.* 2010), which are likely gravitationally unstable (white region) above half the critical value $M_{\rm line,crit} = 2c_{\rm s}^2/G$ (Inutsuka & Miyama 1997). The blue contours outline the 0.1 pc–wide footprints of the filaments (see details in Könyves *et al.* 2015). Right: Same map as in the left panel with the locations of candidate prestellar cores (blue triangles) and protostellar cores (green up-side-down triangles).

gravitationally bound prestellar cores, which may form (proto)stars in the future. We also detected 58 protostellar cores (Könyves *et al.* 2010, 2015; Maury *et al.* 2011).

The comparison of the census of dense prestellar cores and extracted filaments in Aquila suggest their close connection via the core/star formation process. We find that a high fraction of the dense gas mass is in the form of filaments above $A_{\rm V} \sim 7$. Furthermore, $\sim$90% of our prestellar cores are located above an equivalent background column density of $\sim 7 \times 10^{21}$ cm^{-2}, and a similarly high portion of them lie within the densest filaments with supercritical masses per unit length $>16\,M_\odot$/pc (Könyves *et al.* 2015).

Fig. 1 shows the filamentary structure of the Aquila main field, traced by the curvelet transform component (Starck *et al.* 2003) of the column density map in the form of an equivalent stability parameter (mass per unit length) along the filaments. In the left panel the filaments are represented by their 0.1 pc–wide footprints traced with DisPerSE (Sousbie 2011), while in the right panel the candidate prestellar cores and protostellar cores are overplotted. The spatial correlation between the densest filaments and the prestellar cores is strong (see details in Könyves *et al.* 2015).

3. Prestellar CMF and star formation efficiency

In Aquila the core mass function of the large population of prestellar cores confirms earlier findings that the shape of the CMF is very similar to the stellar initial mass function (IMF), and there is a close physical link between the two (Fig. 2/left, Könyves *et al.* 2015).

The local core formation efficiency at the prestellar core level is high in Aquila, $\epsilon_{\rm core} \sim 30 - 40\%$, and only a small fraction ($\sim$15%) of the gas mass is in the form

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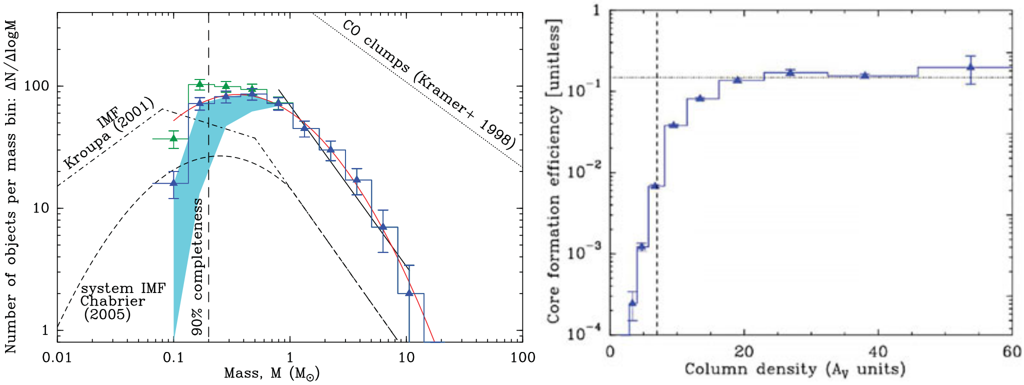

Figure 2. Left: Differential core mass function ($dN/d\log M$) of 651 starless cores (upper green histogram) and 446 candidate prestellar cores (lower blue histogram) identified with *Herschel* in the Aquila field. The shaded area reflects a fraction of $60\% \pm 10\%$ of the starless cores classified as gravitationally bound (see details in Könyves *et al.* 2015). The lognormal fit to the prestellar cores (red curve) peaks at $\sim 0.5\,M_{\odot}$, which is very similar in shape to the IMF of multiple systems (e.g., Chabrier 2005). The power-law fit (black line) has a slope of -1.33 ± 0.06. Right: Histogram of observed differential core formation efficiency (CFE) as a function of background column density in $A_{\rm V}$ units; $\mathrm{CFE_{obs}}(A_{\rm V}) = \Delta M_{\rm cores}(A_{\rm V})/\Delta M_{\rm cloud}(A_{\rm V})$. The vertical dashed line marks the threshold at $A_{\rm V}^{\rm bg} \sim 7$. The horizontal dotted line marks the rough asymptotic value of the CFE $\sim 15\%$, corresponding to a star formation rate per unit gas mass $\sim 5 \times 10^{-8}\,\mathrm{yr}^{-1}$.

of prestellar cores above $A_{\rm V} \sim 7$ (André *et al.* 2014, Könyves *et al.* 2015). Invoking the typical filament width of ~0.1 pc, this observed column density core formation "threshold" corresponds –within a factor of 2– to the threshold above which interstellar filaments become gravitationally unstable (Fig. 1, André *et al.* 2010, 2014).

In order to support further the threshold for core formation we found from the distribution of background cloud column densities of the prestellar cores (e.g., André *et al.* 2014, Könyves *et al.* 2015), we can inspect the observed core formation efficiency (CFE). The right panel of Fig. 2 shows the CFE in Aquila, obtained by dividing the mass in the form of prestellar cores in a given column density bin by the cloud mass observed in the same bin; $\mathrm{CFE_{obs}}(A_{\rm V}) = \Delta M_{\rm cores}(A_{\rm V})/\Delta M_{\rm cloud}(A_{\rm V})$. The observations indicate a very steep rise in the range of $A_{\rm V} \sim 5 - 15$, below which the prestellar CFE is negligible, and approximately constant, above. Despite of the fact that such realizations of the threshold are not infinitely sharp, we argue for the presence of a physical threshold for prestellar core formation around a fiducial value of $A_{\rm V}^{bg} \sim 7$ (André *et al.* 2014, Könyves *et al.* 2015). With *Spitzer*, similar threshold has been observed in the spatial distribution of young stellar objects (YSOs) in nearby clouds (Heiderman *et al.* 2010, Lada *et al.* 2010, 2012, Evans *et al.* 2014).

Altogether, our *Herschel* findings support a picture according to which interstellar filaments and prestellar cores represent two fundamental steps in the formation process of solar-type stars (André *et al.* 2010, 2014): first, the dissipation of kinetic energy in large-scale MHD flows generates ~0.1 pc–wide filaments in the cold ISM; then the densest filaments –above a critical threshold of $\sim 16\,M_{\odot}$/pc in mass per unit length– form prestellar cores (and ultimately protostars) by gravitational instability. The peak of the CMF (at $\sim 0.5\,M_{\odot}$ in Aquila) may also result primarily from the gravitational fragmentation of marginally critical filaments.

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4. Filaments-driven universal star formation law in dense gas?

Our *Herschel* data in the Aquila Rift cloud complex allows us to directly infer the "efficiency" of the star formation process from the physics of prestellar core formation within filaments (see André *et al.* 2014, Könyves *et al.* 2015). The star formation rate per unit mass of dense gas above the threshold is estimated to be $\mathrm{SFR}/M_{\mathrm{dense}} \sim 5^{+2}_{-2} \times 10^{-8}\,\mathrm{yr}^{-1}$ (Fig. 2/right), similar to which was also found independently in nearby clouds by near-/mid infrared studies (Heiderman *et al.* 2010, Lada *et al.* 2010, 2012, Evans *et al.* 2014), and in other galaxies (Gao & Solomon 2004).

These works use different tracers of the dense gas which can make the comparison somewhat uncertain. We also have to bear in mind that the presented star formation processes may be different in some extreme environments, for instance, in the central molecular zone close to the Galactic center, where star formation is known to be more inefficient above the same density threshold (Longmore *et al.* 2013).

In spite of the uncertainties, the similar core formation thresholds may be interpreted as the consequence of the ubiquitous filamentary structure of the nearby molecular clouds, manifesting in a quasi-universal "star formation law" within dense gas above the (column) density threshold (see André *et al.* 2014).

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