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Interstellar filaments and star formation

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ABSTRACT

Recent studies of the nearest star-forming clouds of the Galaxy at submillimeter wavelengths with the *Herschel* Space Observatory have provided us with unprecedented images of the initial conditions and early phases of the star formation process. The *Herschel* images reveal an intricate network of filamentary structure in every interstellar cloud. These filaments all exhibit remarkably similar widths – about a tenth of a parsec – but only the densest ones contain prestellar cores, the seeds of future stars. The *Herschel* results favor a scenario in which interstellar filaments and prestellar cores represent two key steps in the star formation process: first turbulence stirs up the gas, giving rise to a universal web-like structure in the interstellar medium, then gravity takes over and controls the further fragmentation of filaments into prestellar cores and ultimately protostars. This scenario provides new insight into the origin of stellar masses and the star formation efficiency in the dense molecular gas of galaxies. Despite an apparent complexity, global star formation may be governed by relatively simple universal laws from filament to galactic scales.

1. Introduction

Star formation is one of the most complex processes in astrophysics, involving a subtle interplay between gravity, turbulence, magnetic fields, feedback mechanisms, heating and cooling effects (McKee and Ostriker, 2007), etc. Yet, despite this apparent complexity, the net products of the star formation process on global scales are relatively simple and robust. In particular, the distribution of stellar masses at birth or stellar initial mass function (IMF) is known to be quasi-universal (Bastian et al., 2010). Likewise, the star formation rate on both interstellar cloud and galaxy-wide scales is related to the mass of dense molecular gas available by rather well defined "star formation laws" (Lada et al., 2010, 2012; Shimajiri et al., 2017).

This paper presents an overview of recent observational results obtained with the *Herschel* Space Observatory (Pilbratt et al., 2010) and other facilities on the texture of nearby star-forming clouds, which suggest that it may be possible to explain, at least partly, the IMF and the global star formation efficiency in the Galaxy in terms of the quasi-universal filamentary structure of the cold interstellar medium (ISM) out of which stars form. Interestingly, the filamentary web of cold interstellar gas responsible for star formation within galaxies bears a marked resemblance to the cosmic web of intergalactic gas and dark matter leading to galaxy formation in cosmological simulations (cf. Freundlich et al., 2014; Springel et al., 2005 and Section 4 below).

2. Summary of *Herschel* results supporting a filamentary paradigm for star formation

Herschel imaging surveys of Galactic star-forming regions have confirmed the ubiquitousness of filaments

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Fig. 1. *Herschel*/SPIRE 250 μm dust continuum image of a portion of the Polaris flare translucent cloud ($d \sim 150$ pc) taken as part of the HGBS survey (e.g., André et al., 2010; Miville-Deschênes et al., 2010; Ward-Thompson et al., 2010). Note the widespread filamentary structure.

in Galactic molecular clouds (see Fig. 1) and suggested an intimate connection between the filamentary structure of the ISM and the star formation process (André et al., 2010; Molinari et al., 2010). While molecular clouds have been known to exhibit large-scale filamentary structures for quite some time (Schneider and Elmegreen, 1979; Johnstone and Bally, 1999; Myers, 2009 and Myers, 2009), *Herschel* observations now demonstrate that these filaments are truly ubiquitous in the cold ISM (Hill et al., 2011; Men'shchikov et al., 2010; Wang et al., 2015), probably make up a dominant fraction of the dense gas in molecular clouds (Schisano et al., 2014; Könyves et al., 2015), present a high degree of universality in their properties (Arzoumanian et al., 2011), and are the preferred birthplaces of prestellar cores (Könyves et al., 2015; Marsh et al., 2016). This means that interstellar filaments probably play a central role in the star formation process (André et al., 2014).

2.1. A characteristic filament width

Detailed analysis of the radial column density profiles derived from *Herschel* submillimeter dust continuum data shows that, at least in the nearby clouds of the Gould Belt, filaments are characterized by a very narrow distribution of inner widths W with a typical FWHM value ~ 0.1 pc (much higher than the ~ 0.01 pc resolution provided by *Herschel* at the distance ~ 140 pc of the nearest clouds) and a dispersion lower than a factor of 2 (Arzoumanian et al., 2011; Koch and Rosolowsky, 2015; Palmeirim et al., 2013). Independent measurements of filament widths have generally been consistent with this *Herschel* finding when performed in submillimeter continuum emission. For instance, Salji et al. (2015) found an averaged deconvolved FWHM width of $0.08^{+0.07}_{-0.03}$ pc for 28 filaments detected at 850 μm with SCUBA-2. It should be pointed out, however, that significant variations around the mean inner width of ~ 0.1 pc (by up to a factor of ~ 2 on either side) sometimes exist along the main axis of a given filament (Juvela et al., 2012; Ysard et al., 2013). We also note that the report by Henshaw et al. (2017) of a typical width of ~ 0.03 pc for filamentary structures observed in the 1.1-mm dust continuum with ALMA toward the infrared dark cloud G035.39–00.33 may be affected by interferometric filtering of large-scale emission.

Recently, Panopoulou et al. (2017) raised the issue of whether the existence a characteristic filament width is consistent with the scale-free nature of the power spectrum of interstellar cloud images (well described by a single power law from ~ 0.01 pc to ~ 50 pc – Miville-Deschênes et al., 2010, 2016). They suggested that the filament widths obtained by Gaussian fitting may be strongly correlated with the range of radii over which the filament profiles are fitted and may not indicate a genuine characteristic width. This suggestion is questionable for the following reasons. First, simulations indicate that the power spectra of synthetic cloud images including populations of simple model filaments, all 0.1 pc in diameter, remain consistent with the observed 'scale-free' power spectra for realistic distributions of filament contrasts over the background (A. Roy et al., in prep.). Second, in the case of dense filaments whose radial profiles often feature power-law wings, a typical inner diameter of ~ 0.1 pc is also found using a Plummer-like model function of the form $N_p(r) = N^0_{H_2} / \left[1 + \left(r/R_{flat}\right)^2\right]^{\frac{p-1}{2}}$, which provides a much better fit to the overall radial profiles than a simple Gaussian model (see Fig. 2 adapted from Palmeirim et al., 2013). Third, the range of radii used for the Gaussian fitting needs not be arbitrarily fixed, but can be adjusted depending on an initial estimate of the background level at each point along the crest of a filament (André et al., 2016). Finally, it is the *physical* inner width (in pc) that remains approximately constant from filament to filament in *Herschel* observations of nearby clouds, while the *angular* width (in arcsec) scales roughly as the inverse of the parent cloud's distance (Arzoumanian, 2012). Although the width estimates reported for low-density filaments with a low contrast over the background are clearly more uncertain, we conclude that the median FWHM filament width of 0.09 ± 0.04 pc reported by (Arzoumanian et al., 2011 – see also André et al., 2014) is most likely reflecting the presence of a genuine characteristic scale corresponding to the inner diameter of filament systems, at least in the Gould Belt.

The existence of this characteristic scale is challenging for numerical simulations of interstellar cloud turbulence (Smith et al., 2014; Ntormousi et al., 2016), and the origin of the common inner width of interstellar filaments is currently debated. A possible interpretation is that filaments originate from planar intersecting shock waves due to supersonic interstellar turbulence (Pudritz and Kevlahan, 2013) and that the filament width corresponds to the (magneto-)sonic scale below which the turbulence becomes subsonic in diffuse, non-star-forming molecular gases (Federrath, 2016; Padoan et al., 2001). Alternatively, a characteristic width may arise if interstellar filaments are formed as quasi-equilibrium structures in pressure balance with a typical ambient ISM pressure $P_{ext} \sim 2\text{–}5 \times 10^4\,\mathrm{K \cdot cm^{-3}}$ (Fischera and Martin, 2012; S. Inutsuka, private communication). A second alternative explanation relies on the thermodynamical properties of