

Star formation in the solar neighbourhood

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Abstract. Star formation started as a cosmic process soon after the big bang and still continues in the Milky Way, although at a decreasing rate. The formation of dense interstellar clouds, their fragmentation and eventual collapse lead to the birth of stars. The nearby clouds provide the highest resolution for the study of this process. The progress is closely following the improvement of the infrared and radio-wavelength facilities that enables us to follow even the earliest stages of the star-formation process inside molecular clouds. On the other hand, modern numerical simulations can take into account most of the relevant physics and often provide a more direct access into the general principles of star formation. The comparison of observations and simulations is therefore essential. In this paper, will discuss star formation in the solar neighbourhood, concentrating on the prestellar phases leading up to the formation of protostars.

Keywords. stars: formation, ISM: clouds, ISM: kinematics and dynamics, ISM: structure, ISM: magnetic fields, dust, extinction, infrared: ISM, radio lines: ISM, submillimeter

1. Nearby molecular clouds

There are many nearby molecular clouds at distances just beyond 100 pc (see Fig. 1). Because most instruments, for example single-dish radio telescopes, provide an angular resolution better than ~ 1 arcmin, star formation in these clouds can be studied from clouds scales (sizes > 1 pc) to clumps (~ 1 pc) and down to the structure of gravitationally bound cores (~ 0.1 pc) (Bergin & Tafalla 2007). The nearby clouds have a central role when we try to understand the formation of low and intermediate mass stars.

Many of the best-studied clouds belong to the Gould Belt. This structure is tilted by some 20° with respect to the Galactic plane and was first recognised in the distribution of bright stars in the southern sky. B.A. Gould referred to it already in 1874 (Gould 1874) and wrote in his *Uranometria Argentina*: “Thus I cannot avoid the conviction that our own system forms part of a small cluster, distinct from the vast organization of that forms the Milky Way...” (Gould 1879). This is not very far from the current understanding. The belt is not only a stellar structure but also a location of on-going star formation, containing regions such as the Taurus-Perseus-Auriga complex (distances $d \sim 100 - 500$ pc), the ρ Ophiuchus cloud ($d \sim 150$ pc), and the Orion region ($d \sim 400$ pc).

Recent observations have provided a wealth of new information on the nearby clouds. Even now, the data are still revealing entirely new phenomena that are related to the structure of the clouds and the final stages of the prestellar evolution.

2. Observations of nearby clouds

Ground-based observations of molecular lines and dust continuum extend from radio wavelengths (Myers *et al.* 1983, Motte *et al.* 1998) to sub-millimetre (Ward-Thompson *et al.* 2000, Shirley *et al.* 2000). The past two decades have seen a number of space-borne instruments that have complemented these data with infrared and sub-millimetre observations of unprecedented sensitivity. These include satellites such as ISO (Kessler *et al.* 1996; e.g. Tóth *et al.* 2000), Spitzer (Werner *et al.* 2004), AKARI

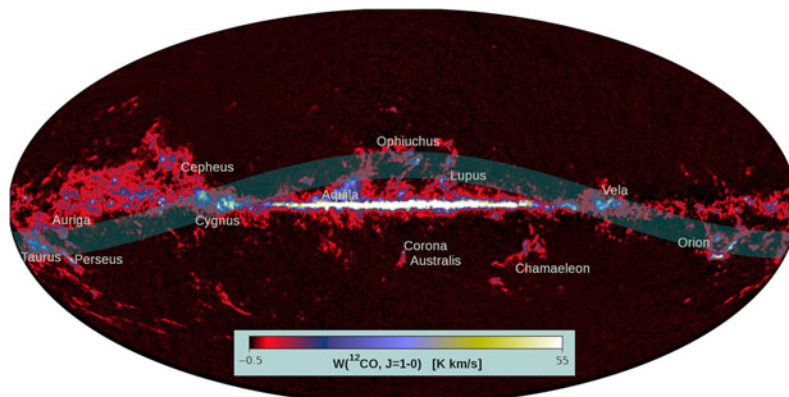


Figure 1. Some nearby molecular clouds marked on the all-sky CO line emission map derived from Planck measurements (Planck Collaboration 2014). These clouds are important targets of star-formation studies, thanks to their typically small distances (100 - 500 pc). Many of the clouds belong to the Gould Belt system (Gould 1879) that is indicated with a cyan band.

(Murakami *et al.* 2007), and WISE (Wright *et al.* 2010). The combination of different instruments makes it possible to follow the full evolution from cold prestellar clouds to protostellar cores, before the young stellar objects (YSOs) again come within the reach of ground-based near-infrared telescopes. Together the ground-based and the space-borne infrared instruments have also made it possible to catalogue YSOs in the nearby clouds and even over the whole sky.

The Herschel Space Observatory (Pilbratt *et al.* 2010) has made a particularly large impact on star-formation studies. It mapped the whole Galactic plane (Molinari *et al.* 2010) and most nearby molecular clouds (André *et al.* 2010) and regions of high-mass star formation (Motte *et al.* 2010). The multi-frequency sub-millimetre continuum data literally shed new light on the star-formation problem by showing the intricate, extended density structures around the star-forming cores. This is in contrast with ground-based continuum surveys where the angular resolution is usually higher but the imaging of extended emission is more challenging (Schuller *et al.* 2009; Ward-Thompson *et al.* 2016). Herschel also carried out heterodyne observations of many key lines that are inaccessible from the ground (e.g. Mottram *et al.* 2014, Goicoechea *et al.* 2015).

One should also not forget extinction measurements from optical to mid-infrared wavelengths (Cambrésy 1999, Bacmann *et al.* 2000, Alves *et al.* 2001). These provide an important point of comparison by being independent of dust temperature. Near-infrared extinction also appears to be little affected by dust evolution compared to the variations seen in the long-wavelength dust opacity (Cardelli *et al.* 1989, Wang & Jiang 2014). With ground-based surveys one can cover everything from diffuse regions ($A_V < 1$ mag) to cores with tens of magnitudes in A_V (Kandori *et al.* 2005, Juvela *et al.* 2008). Nearby clouds have thus been studied combining emission and extinction (Cambrésy *et al.* 2001, Lombardi *et al.* 2006, 2014, Meingast *et al.* 2018) and even all-sky extinction maps exist. The ambiguity resulting from the line-of-sight (LOS) mixing of the stellar and interstellar matter distributions is being addressed with 3D extinction mapping methods (Marshall *et al.* 2009, Green *et al.* 2018, Lallement *et al.* 2018).

While space instruments provide improved sensitivity and wavelength coverage, ground-based telescopes still excel in resolution. Radio interferometers, especially ALMA, are revealing new details in the density structure, kinematics, and chemistry of star-forming clouds at the very smallest scales (Kainulainen *et al.* 2017, Hacar *et al.* 2018) and especially at the protostellar phases (e.g. Cox *et al.* 2018).

3. Structure of star-forming clouds

Herschel made cloud filaments a central topic of star-formation studies. Naked-eye observations of dark nebulae go back to William Herschel (Herschel 1785) but the first observations of elongated cloud structures came with astrophotography. E. E. Barnard commented on the *dark lanes, streaks, and thin threads* visible in his photographs (Barnard 1910). Already in 1894, A.C. Ranyard described the ρ Ophiuchus images as showing “*dark vacant areas or channels. . . seem to me to be undoubtedly dark structures, or obscuring masses in space, which cut out the light from the nebulous or stellar region behind them*”. Barnard cautiously agreed that these were caused by matter in the interstellar space. The appearance of Pleiades and the Orion nebula was suggestive of a connection between the filamentary nebulosities and stars. Theoretical studies of filament fragmentation and star formation in this context go back at least 70 years (Edgeworth 1946).

Although filaments were later seen in simulations of hydrodynamical and magnetohydrodynamical turbulence (e.g. Padoan *et al.* 2001) they were less evident in observations and only rarely a central topic in star-formation studies (Elmegreen & Elmegreen 1979, Bally *et al.* 1987, Enoch *et al.* 2007). This changed fundamentally with Herschel (the satellite). By imaging large areas with a sensitivity far exceeding that of ground-based instruments (down to below $N(\text{H}_2) = 10^{21} \text{ cm}^{-2}$), it showed the extensive filamentary networks in both diffuse clouds and actively star-forming regions (André *et al.* 2010, Miville-Deschênes *et al.* 2010, Arzoumanian *et al.* 2011).

The radial profiles of the filaments are observed to be flat compared to the $\rho \sim r^{-4}$ behaviour predicted for isothermal cylinders in hydrostatic equilibrium (Stodólkiewicz 1963, Ostriker 1964). This suggests effects of temperature variations or magnetic fields – or that filaments indeed are not static structures (Kawachi & Hanawa 1998, Nakamura & Umemura 1999, Fiege & Pudritz 2000, Palmeirim *et al.* 2013; Arzoumanian *et al.* 2013). The filaments of nearby clouds also appear to have a narrow distribution of widths, $\sim 0.05 - 0.2 \text{ pc}$ (Arzoumanian *et al.* 2011; Rivera-Ingraham *et al.* 2016). However, in images one can readily see structures at different scales (Fig. 2). Thick filaments may consist of sub-filaments and the width can vary along the filaments, possibly correlated with the column density and core formation (Juvela *et al.* 2012a, Heigl *et al.* 2018). Width measurements are complicated by the varying background, radiative transfer effects, and the finite resolution of the observations (Juvela *et al.* 2012b, Panopoulou 2017, Ossenkopf-Okada & Stepanov 2019). Nevertheless, the observations have led to attempts to theoretically explain the preferred filament widths (e.g. Fischera & Martin 2012; Hennebelle & André 2013, André *et al.* 2014; Xu & Lazarian 2019).

Molecular line observations revealed in some filaments velocity-coherent substructures that were coined fibers (Hacar & Tafalla 2011). Without full 3D information, detections in the position-position-velocity (PPV) space might suffer from LOS confusion and a PPV structure might not necessarily be identifiable in 3D density (Clarke *et al.* 2018). However, interferometric observations have detected fibers of high column density, narrow width, and almost subsonic velocity dispersion. This suggests that the fibers represent another step closer to the actual star formation (Hacar *et al.* 2018; Monsch *et al.* 2018).

Low-column-density striations are observed perpendicular to the major axis of some more massive structures (Peretto *et al.* 2013; Cox *et al.* 2016). These can be seen also in line emission, for example in Taurus (Heyer *et al.* 2016). The correlation with polarisation suggests a close connection to the magnetic fields. Observations and simulations show that massive filaments tend to be perpendicular to the magnetic field while low-density structures are preferably parallel (Planck Collaboration *et al.* 2016b, Malinen *et al.* 2016, Soler & Hennebelle 2017). Striations could thus represent accretion onto filaments. This is seen in some simulations but is difficult to quantify in observations because of the unknown inclination (Vestuto *et al.* 2003, Palmeirim *et al.* 2013; Chen *et al.* 2017).

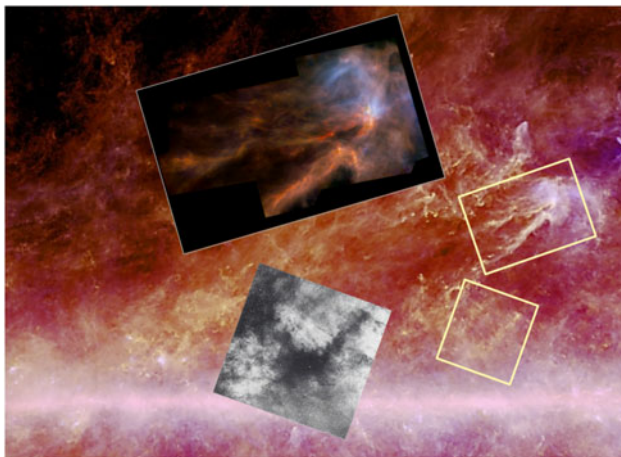


Figure 2. Filamentary clouds in the Ophiuchus region. The background shows surface brightness measurements from Planck (Planck Collaboration 2016a) combined with IRAS 100 μm data (credits: ESA/HFI Consortium/IRAS). The zoom-ins show the main ρ Oph cloud (upper box and inset) as seen with Herschel (credit: ESA/Herschel/NASA/JPL-Caltech, R. Hurt 2017), and the Pipe nebula photographed by E.E. Barnard some 110 years earlier (Barnard 1926).

The projected shape of clouds is known accurately from observations but, in the LOS direction, we are only now starting to get constraints from 3D extinction mapping and from YSO and field star distance measurements (Green *et al.* 2018, Galli *et al.* 2018, Großschedl *et al.* 2018). The situation could be better for cloud sub-structures if one could assume that these follow some symmetries. Cores and clumps are often modelled with radial density distributions (Shirley *et al.* 2000, Juvela *et al.* 2018). These may be adequate for quasi-static cores but, because clumps do have sub-structure, spherical models only provide a statistical characterisation of these objects.

Similarly, Herschel filaments are known to have internal structure that is not detected in low-resolution data or without the benefit of velocity information. One may also ask whether they are more cylindrically symmetric objects or sometimes only tangential projections of two-dimensional sheets. The large contrast between the (star-forming) filaments and the background and the quasi-uniform width would seem to argue against the sheet hypothesis. If the structures were extended in the LOS direction, we would also not see such a clear connection between the filaments and the striations. More directly, measurements of high volume densities can show that the mass seen in column density is concentrated in a small volume (Shimajiri *et al.* 2019). Objects such as the Musca cloud contain, or partly even consists of, clumps that have a structure reminiscent of Bonnor-Ebert spheres (Juvela *et al.* 2010). If the filaments were only 2D projections, the alignment between clumps and the filaments would be worse. The same argument applies to the tight spatial correlation with the prestellar and protostellar cores. Filaments may reside in sheets or be the product of sheet collisions but at least the dense ones appear to be closer to the cylinder symmetry. However, the cylindrical shape is only a very crude approximation of the complex structure of the real filaments.

4. Birth of prestellar cores

Cloud fragmentation leads to the formation prestellar and protostellar cores (see the review by C. Federrath in this issue). These are found in regions with background column densities above $N(\text{H}_2) \sim 5 \times 10^{21} \text{ cm}^{-2}$ ($\Sigma \sim 110 \text{ M}_\odot \text{ pc}^{-2}$) (André *et al.* 2010; Lada *et al.* 2010; Montillaud *et al.* 2015; Marsh *et al.* 2016). Since star formation progresses from atomic clouds to stellar densities, it would seem that almost any “threshold” could be

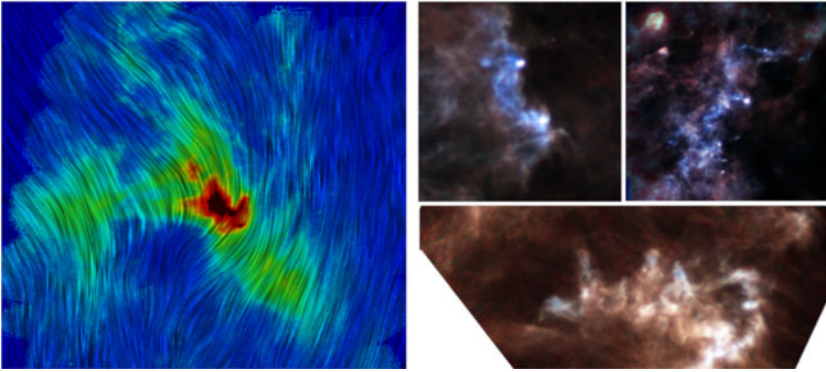


Figure 3. *Left:* Herschel intensity map of the star-forming cloud LDN 1642. The line integral convolution (LIC) pattern shows the plane-of-the-sky magnetic field orientation based on the 353 GHz Planck data (Malinen *et al.* 2016). *Right:* Herschel images of three star-forming clouds where the filamentary structure is strongly modified by external forces (Juvela *et al.* 2012a).

selected by concentrating on a different size scale. However, the coincidence with the threshold of filament stability suggests that this limit is of a more fundamental nature.

The spatial distribution of protostellar sources is strongly associated to supercritical filaments (Könyves *et al.* 2015, Marsh *et al.* 2016, Rivera-Ingraham *et al.* 2017, Bresnahan *et al.* 2018). Isothermal filaments should fragment when the mass per length exceeds the critical value, $M_{\text{crit}} = 2 c_s^2/G$, but one should take into account also the effects of internal non-thermal motions, external pressure, magnetic fields, the non-uniform turbulent environment and other external agents (see Fig. 3) – and the dynamical nature of the filaments themselves (Inutsuka & Miyama 1997; Fiege & Pudritz 2000, Myers *et al.* 2009, Heitsch *et al.* 2011, Seifried & Walch 2015, Haugbølle *et al.* 2018).

Cloud and filament properties show systematic trends but each cloud is individual and during its lifetime may be subjected to stellar winds and repeated supernova shocks (Peretto *et al.* 2012; Inutsuka *et al.* 2015). The conditions set by random density and velocity fluctuations affect the structure and the fragmentation. Although, e.g. the observed fragmentation lengths are often attributed to some gravitational or MHD instability, it is not surprising that real clouds do not strictly follow the theoretical predictions (Beuther *et al.* 2015, Roy *et al.* 2015, Contreras *et al.* 2016, Kainulainen *et al.* 2017).

Star formation is characterised by the star-formation efficiency (SFE) and the stellar initial mass function (IMF). To explain the origin of these, one must characterise the preceding step, the prestellar cores, looking at the corresponding core formation efficiency (CFE, the fraction of cloud mass converted into cores) and core mass function (CMF) (Motte *et al.* 1998, Kiss *et al.* 2006, Alves *et al.* 2007). CFE estimates vary in wide range (at least 5 - 35%) between different clouds, probably also depending on the observations used and the chosen extent of the region (Palau *et al.* 2013, Zhang *et al.* 2019, Kong *et al.* 2018). Many studies have commented on the similarity of the IMF and the prestellar CMF after a $\sim 30\%$ relative shift (efficiency) in masses (e.g. Marsh *et al.* 2016; Sokol *et al.* 2019). Compared to the local clouds, CMF seems to be flatter in high-pressure environments and regions of high-mass star formation (Liu *et al.* 2018). However, it is still unclear how sensitive (or insensitive) the CMF is to the local cloud conditions.

5. Outlook

Many open question remain concerning star formation in the solar neighbourhood. How are the filaments formed, how do they acquire their final mass, what governs their fragmentation to cores, and what are the lifetimes of all the objects? This should depend on whether evolution is driven mainly by turbulence or gravity, whether external forces

(radiation, stellar winds, and supernovae) are important, and what role the still poorly known magnetic fields have (Fig. 3). This complexity makes it difficult to determine the environmental differences that would explain cloud-to-cloud variations of the SFE and the IMF, to the extent they indeed exist. It also limits the generality of the conclusions that can be drawn from any limited cloud sample. This may apply even to the entire sample of nearby clouds, where the influence of massive stars is limited.

Unlike simulations, observations cannot be used to follow the formation of a star from start to finish. We only have a series of snapshots of different environments in different stages of evolution. This has not prevented the determination of many generalities, from the statistics of the large-scale density field (e.g. Kainulainen *et al.* 2009) to the CMF properties. Progress clearly needs close collaboration between observers and modellers. We should also reach a point where, instead of only comparing observations to random model realisations, accurate models are developed for the real individual clouds.

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Discussion

ALFARO: Could you estimate the expected lifetime of filaments?

JUVELA: Filaments are fragmenting to cores and the lifetime of a core is known to be at least ~ 1 Myr. Clouds live at least a few million of years, so the lifetime of a filament must be in the same ball park

KHAIBRAKHMANOV: Filaments are cylinders or sheets? Can we distinguish between these structures?

JUVELA: Regarding cylindrical shape, filaments are likely cylinders. But it is not easy to determine their shape from observations. For some filaments, the volume density has been estimated from molecular lines, which suggest they are cylinders more than sheets.

ZINNECKER: Herschel observations put the filamentary structure of the dense interstellar medium into the limelight. However, in the historical context, who is to be credited with the filamentary nature of dark clouds?

JUVELA: Some credit should certainly be given to Barnard, who drew attention to these elongated structures within the ISM – even if he may not have used the filament word to describe them.

TÓTH: Filaments are usually seen as 2D objects. How much we can trust these are real objects and not just projections?

JUVELA: Simulations have shown that projection effects play a role and especially the filaments seen in continuum are not necessarily single objects in 3D. They may be the superposition of several structures that are not physically connected. However, in the case of such filaments like Musca, it is very likely to be a single object, a real filament.

MAROV: Did you find any correlation between line slopes and fiber/filament structure?

JUVELA: Line profiles can be used to search for signs of collapse - but in the case of fibers, it is just their velocity, they being velocity-coherent in the ppv space.

HACAR: The fibers have narrow lines with clearly subsonic linewidths.