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The role of automated methods for filament finding in understanding the complex relationship between filaments, magnetic fields and star formation

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Abstract. The discovery of the ubiquity of filaments in the interstellar medium in the last two decades has begged the question: "What role do filaments play in star formation?" Here we describe how our automated filament finding algorithms can combine with both magnetic field measurements and high-resolution observations of dense cores in these filaments, to provide a statistically large sample to investigate the effect of filaments on star formation. We find that filaments are likely actively accreting mass from the interstellar medium, explaining why some 60% of stars, and all massive stars, form "on-filament".

Keywords. Stars: formation, ISM: molecules.

1. Introduction

The way we do astronomy, particularly radio, millimetre and sub-millimetre astronomy, is rapidly changing. In the not too distant past, a small group of astronomers would apply for time on a telescope, for a particular project with a relatively narrow science focus, travel to the telescope, take the observations, reduce and analyse them, and with some luck produce a refereed journal paper in around three years.

Now, cutting-edge telescopes and observatories, such as the Atacama Large Millimeter Array (ALMA) and the future Square Kilometre Array (SKA) (Sundaram 2015), are funded by many entities and nations. The vast world-wide investment in these telescopes, and the importance of computing power and specialised knowledge in both collecting and reducing the observations, means that many astronomers will not collect the data that they will use for their research. Instead the job of collecting and reducing data is now done by experts in this area.

On the other hand, the quantity and quality of data collected by these new telescopes is unprecedented, leading to a tsunami of high-quality data that is currently ready to be analysed. The amount of data available is far more than any one individual can analyse by hand, and in any case, such an analysis would be a poor use of the large data sets available for exploitation.

So, we now need to automate data analysis processes, so that the large amount of high-quality, reduced data available is exploited to maximise the science.

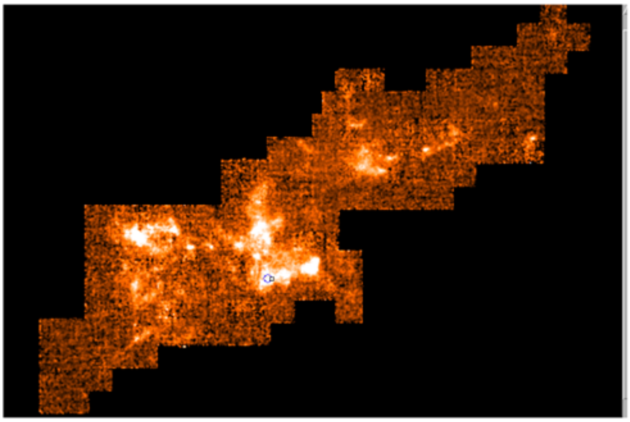

Figure 1. Image of the integrated emission of the HCN(1–0) transition in the Vela C molecular cloud. The filamentary structure is obvious upon visual inspection of this image. However, images of other molecules, and dust such as in the Herschel HOBYS project show similar, but still different, filamentary structure. This highlights the difficulty of defining what is physically a filament. The black outline structure seen in the middle lower part of the image, on the filament described as the "south ridge" shows a particularly dense condensation in this filament (Lowe 2014).

In this paper we describe how automated filament finding in the molecular interstellar medium (ISM) has contributed to our understanding of the relationship between filamentary structure in the ISM, magnetic fields and star formation. We also discuss upcoming surveys which will use automated filament finding and other automated data analysis techniques to extend our analysis, to provide more robust results. It is possible that the relationship between filaments, gravity and turbulence may have different outcomes in differing parts of the Milky Way galaxy (see e.g Luna *et al.* 2006).

2. Filaments in the interstellar medium

The discovery that filaments were significant structures in the ISM cannot be attributed to any one survey, but developed over time (see e.g. Ntormousi *et al.* 2016, and references therein). However, the advent of the Herschel Space telescope cemented the place of filaments as fundamental ISM structures that are important in the star formation process (see e.g. André *et al.* 2010).

So, as Herschel and other large-scale spatial surveys became available, it became important to define exactly what a filament is, and how it was differentiated from the rest of the molecular ISM, in an automated way (Green *et al.* 2017a; 2017b)

Green *et al.* (2017a; 2017b) described a "Goodness-of-Fit" measure that was shown to alleviate visual bias in filament identification, and also automated the determination of the angle between filament elongation and magnetic field direction.

The Vela C molecular line survey of the Mopra telescope†, in Australia, was used to test the filament finding algorithm (Green *et al.* 2017a), along with Herschel HOBYS data of the Vela C molecular cloud (Hill *et al.* 2012). The Mopra Vela C survey is described most completely in Lowe (2014). This survey covered molecular lines from 20 to 116 GHz, detecting some dozens of different molecular transitions. Figure 1 shows the filaments in this region as traced by the Mopra telescope observations of the HCN(1–0) transition. The same data was used to test the automated determination of the angle

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† The Mopra telescope, in Coonabarabran, northern NSW, was at the time these observations were taken, run by the CSIRO Australia Telescope National Facility.

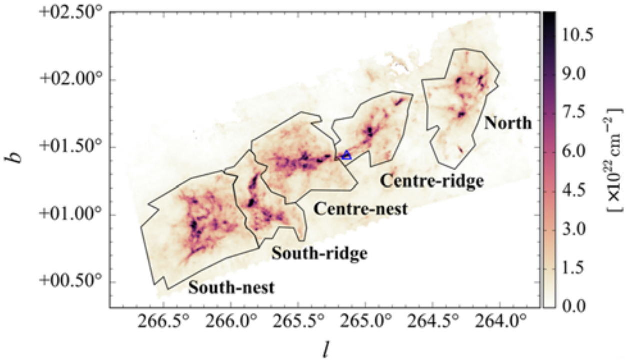

Figure 2. The filamentary regions of Vela C. Presented is the Fissel *et al.* (2016) dust-derived column density map of Vela C overlaid with the different subregions designated by Hill *et al.* (2011). The small triangle marks the position of the RCW 36 IR star cluster (Ellerbroek *et al.* 2013).

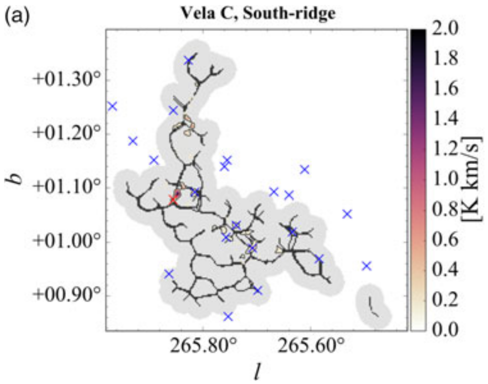

Figure 3. Filamentary structure in Vela C, as determined by the algorithms discussed above. Overlaid on the combined skeletons (in dark grey) are ATCA clumps (small ellipses matching the scale of the colourbar) and the Giannini *et al.* (2012) pre- and protostellar sources, marked by crosses. The light grey represents the average spatial filament extent. See Green 2017 for a high-resolution version of this image.

between filamentary structure and the magnetic field in Vela C, the latter determined from the BLASTPol balloon-borne polarimeter (see e.g Novak 2019).

Figure 1 can be compared with Figure 2, which shows the dust-derived column density map of the Vela C region (Fissel *et al.* 2016). With this comparison, it becomes obvious that different tracers of dense molecular gas give different visual indicators as to the position and extent of filamentary structure.

3. Conclusion and Summary

The automated techniques described in Green *et al.* (2017a, 2017b) can robustly define filaments, using a combination of dust and molecular line data. Figure 3 shows the results of the application of these techniques to the Southern Ridge in Vela C.

Here we summarise the results of the papers mentioned above:

- Filaments are preferred sites for star formation, with ∼65% of stars forming on filaments. All massive stars form on filaments.
- Filaments collapse along magnetic field lines
- When stars form on filaments, the direction of collapse is perpendicular to the magnetic fields.
- These results agree with many theoretical predictions (see e.g. Gómez *et al.* 2018).

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