Analysis of the probability density distribution in star-forming clouds

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Stars are born in dense, coherent regions of the cold molecular phase of the interstelar medium called molecular clouds (MCs). Thus the study of star formation requires understanding of the morphological and kinematical evolution of MCs.

At the initial stage of MC formation the warm atomic gas is compressed by supersonic flows and cools down rapidly due to non-linear thermal instabilities, reaching temperatures as low as $10-30$ K, number densities $\sim 100\ \ \mathrm{cm}^{-3}$ and turbulent Mach numbers $\mathcal{M} \sim 20-30$. Initially, MCs are not in equilibrium and evolve towards equipartition between the turbulent and the gravitational energy. Stars begin to form at a later evolutionary stage when self-gravity takes slowly over and local sites of gravitational collapse emerge (Vázquez-Semadeni et al., 2007). This evolution of MCs could be traced, e.g., in terms of the physical parameters of MC fragments (clumps, cores, filaments) and their scaling relations (Larson, 1981; Veltchev et al., 2018) or through investigation of the general cloud structure in terms of abstract scales (Heyer & Brunt, 2004; Veltchev, Donkov & Klessen, 2016).

An often used approach to investigate the physics of star-forming regions (SFRs) is the analysis of the probability density function (PDF) of mass density (ρ-PDF) and column density (N-PDF). It has been shown from theoretical modelling (Vázquez-Semadeni, 1994) and confirmed by subsequent numerical studies (e.g., Padoan et al., 1997; Klessen, 2000) that supersonic turbulence in an isotermal medium with negligible gravity produces a lognormal ρ-PDF. As self-gravity becomes important in the energy balance of the cloud, a power-law tail (PLT) with negative slope forms at the high-density end of the ρ-PDF (Kritsuk, Norman & Wagner, 2011; Burkhart et al., 2017). At the stage of ongoing local collapses in the cloud, the PLT slope gets shallower and tends toward some constant value while the deviation point (DP) from the main, quasi-lognormal part of the ρ-PDF shifts toward lower densities (Girichidis et al., 2014; Veltchev et al., 2019). The N-PDF in star-forming clouds can be directly derived from observations and turns out to be morphologically similar to the ρ-PDF: with a lognormal main part including the peak and a PLT at the high-density end (Schneider et al., 2013, 2015a), as found also from numerical studies of self-gravitating, contracting clouds (Ballesteros-Paredes et al., 2011; Federrath & Klessen, 2013). To sum up, the formation and development of PLTs both in ρ-PDF and N-PDF in evolved star-forming MCs is a well established phenomenon. The complex physics of evolved MCs is implemented in the parameters of the PLT: slope and DP.

In the present PhD thesis, we propose and develop an objective method for extracting PLTs from ρ-PDF and N-PDF in SFRs. The method is based on a statistical approach to obtain presumed power-law approximations of a part of data distribution developed by Clauset, Shalizi & Newman (2009) and Virkar & Clauset (2014), with PLT slope and DP being determined simultaneously.

In Chapter 2 we briefly comment on other used approaches to extract a PLT and justify the need of a method for reliable derivation of the PLT parameters, independent on assumptions about the main PDF part or a chosen binning scheme. We propose an adapted method (AM) bPlfit (Veltchev et al., 2019) and show its reliability when applied to numerical data for SFRs at galactic ($\sim$0.5 kpc; SILCC) and at clump scales in MCs ($\lesssim$0.5 pc; HRIGT). The method's sensitivity to a chosen map frame or to the choice of isocontour to delineate clouds from the SILCC simulations is also investigated (Marinkova et al., 2020a). The results are compared with those obtained for the entire simulation cube. In Chapter 3 the AM bPlfit is elaborated further to detect a second PLT (if present) with a different slope in the range of very higher densities. The method was tested on analytical data to assess its effectiveness and was subsequently used for analysis of ρ-PDF from numerical data at scales of typical large clumps and the N-PDF from *Herschel* observations.

The concluding Chapter 4 summarizes the main results as follows:

- *Evolution of the PLT parameters*: The PLT slopes of ρ-PDF in late stages of MCs evolution tend to $q \sim -1.5$, for both SILCC and HRIGT data. On the other hand, the PLTs of N-PDF obtained from *Herschel* observations have slopes $-2 \leq n \leq -4$.
- *Analysis of N-PDF in giant MCs at advanced evolutionary stage*: Two MCs are chosen in areas of increased resolution from SILCC simulations, allowing to assess possible boundary effects on the PLT parameters from the chosen area delineation. For this purpose, the PLT evolution was followed by use of two different approaches: 1) imposing 4 rectangular frames of increasing size, encompassing the selected GMCs and the low density gas in their immediate vicinity; and 2) within an isocontour defined by a lower limit of N that is less than the average DP determined from PLT analysis done at 1). The obtained PLT parameters in all rectangular frames, at a given evolutionary stage, are very similar. This means that the low-density H_2 located outside the main filaments of the giant MCs does not contribute to the PLT range. The PLT slope of the N-PDF in the isocontour remains almost constant in time ($n \geq -1.2$): much shallower than expected from theoretical studies of self-gravitating MCs ($n \sim -2$), as well from observations of SFRs. Possible explanation: the PLT evolution of H_2 does not necessarily follow the same pattern like the one obtained from maps of the total (molecular and atomic) gas (Vázquez-Semadeni, 2010).
- *Extraction of a second PLT* (Marinkova et al., 2021): The idea is based on the dependence of the PLT parameters on the chosen lower cutoff of the distribution; varying this limit, one is able to detect two different PLTs. The extracted second PLT must span at least one order of magnitude, with slope which differs by ≥ 0.4 from the one of the first PLT. In all but one studied cases from HRIGT two PLTs were detected – the second one is flatter, with $q \sim -1$. These results are in good agreement with expectations from numerical (Kritsuk, Norman & Wagner, 2011) and theoretical (Girichidis et al, 2014) studies. We also applied the new AM bPlfit to

observational data for several regions of active star formation obtained by *Herschel* (Marinkova et al., 2020b).

Applying the AM bPlfit to ρ-PDF or N-PDF from high-resolution numerical simulations or/and observations of SFRs can elucidate the physical conditions in the densest substructures of evolved MCs.

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