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Molecular cloud formation, turbulence and feedback

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Abstract. This contribution is an update of the review *Turbulent molecular clouds* by Hennebelle & Falgarone (2012). Particular emphasis is given to the recent theoretical progress regarding the understanding of density probability density function (PDF), filament formation and fragmentation, cluster formation and feedback as well as the efforts toward getting self-regulated global interstellar medium (ISM) models at the kpc scale.

Key words. Instabilities – Interstellar medium: kinematics and dynamics – structure – clouds – Star: formation

1. Introduction

The interstellar cycle, which takes place within galaxies, is fundamental for our universe as it controls the formation of stars and therefore the evolution of galaxies. Yet given the broad range of spatial scales and the profusion of physical processes involved, our understanding is still very incomplete. The present contribution is an update of the review by Hennebelle & Falgarone (2012) that was initiated by Francesco Palla and which emphasized the role of turbulence in molecular clouds. Only recent studies are therefore covered here and systematic reference to Hennebelle & Falgarone (2012) is made. In particular, due to limited space, many references cannot be repeated but can be found in this review. For the same reason, most of the details regarding the results and physical processes mentioned below could not be presented, short descriptions are given instead.

The plan of the paper is as follows. First we review the recent progress which has been made regarding the density PDF in molecular clouds. Then sections 3 and 4 discuss some of the structures that form in molecular clouds, more precisely the filaments and the protoclusters. Section 5 describes the global models which have been developed recently to provide a self-consistent ISM. Section 6 concludes the paper.

2. Theoretical understanding of the density PDF

The density PDF is playing an important role in the ISM particularly for the star formation process. Various models aiming at explaining the initial mass function of stars (Hennebelle & Chabrier 2008) or the star formation rate (Hennebelle & Falgarone 2012; Federrath & Banerjee 2015) relies on the density PDF. As such it is receiving much attention and a *standard model* has emerged from both theory and observations (Hennebelle & Falgarone 2012).

The density corresponding to cold and weakly self-gravitating molecular gas has typically been found to be lognormal likely as a result of the random shocks induced by the compressible turbulence and the multiplicative nature of density leading to a Gaussian distribution of $\log \rho$. An interesting approach has been proposed by Hopkins (2013), who inferred a log-Poisson distribution for the density field, applying intermittent models developed for incompressible turbulence. The distribution he obtained possesses a free parameter that controls the degree of intermittency and the deviation from the lognormal distribution. Hopkins (2013) performed a systematic comparison with PDF from numerical simulations and found very good agreement in particular for the high Mach number simulations which present strong deviations from the lognormal behaviour particularly when compressive forcing is applied. Another important question regarding the cold and non-self gravitating gas is the cooling. Most of the works so far made the isothermal assumption while powerlaws instead of lognormal have been reported for polytropic flows. Federrath & Banerjee (2015) have conducted a series of high resolution simulations for polytropic flows, i.e. following $P \propto \rho^{\Gamma}$ for $\Gamma = 0.7$, 1 and 5/3. They found limited differences between $\Gamma = 0.7$ and 1 that do not strongly deviate from a lognormal. Clear deviations were obtained for $\Gamma = 5/3$ in particular the low density part of the PDF is better described by a powerlaw. The density variances can be reproduced well using a simple model of polytropic shock. Federrath & Banerjee (2015) also computed the expected star formation rate using analytical estimates based on the PDF and found that values about 5 times larger with $\Gamma = 0.7$ than for $\Gamma = 5/3$.

In presence of self-gravity, it has been found that a powerlaw tail of high density material develops. Typically the exponent of the powerlaw has been found to be about -1.5 and a simple explanation based on the density profile $\propto r^{-2}$, where r is the distance from the cloud center, was been put forward. Girichidis et al. (2014) have been analysing this in great details performing both simulations and analytical calculations and confirmed this conclusion.

Burkhart et al. (2017) (see also Myers 2015) considered a model for the column density distribution that is composed of a lognormal and a powerlaw. They computed the transition point by requiring continuity and derivability of the distribution and have confronted the resulting PDF with numerical simulation results finding good agreement.

3. Filaments

While the density PDF provide very important information on the ISM, it should be kept in mind that they miss an essential piece of information, which is the spatial correlations in other words the shape of the interstellar clouds. While it has since long been recognized that the ISM is remarkably filamentary, recent studies carried out by Herschel led to quantitative statistical estimates of their properties (André et al. 2014).

The first question that has to be addressed is what is the origin of this ubiquitous filamentary structure ? Second Herschel studies have also revealed that the filaments have a possible characteristic width of about 0.1 pc, which is surprising and needs to be explained. Finally, it seems that most star forming cores sit inside self-gravitating filaments, seemingly suggesting that filaments may be one decisive step of the star formation process.

3.1. Formation of filaments

It is well known that gravity amplifies anisotropies and tends to promote the formation of filaments. In the context of molecular clouds this is particularly evident in studies like the ones performed by Smith et al. (2014), Gómez & Vázquez-Semadeni (2014), Federrath (2015) and Camacho et al. (2016). This is simply because the gravitational force being the gradient of a scalar, it is stronger along the shortest axis of a clump. However, gravity can not explain all the observed filaments because many filaments are not self-gravitating. Indeed, the atomic gas (HI) is itself rather filamentary but is far from being self-gravitating. It seems therefore that other processes could lead to filament formation.

To investigate this issue Hennebelle (2013) performed MHD and hydrodynamical turbulent simulations of the ISM and computed the clump aspect ratio. He concluded that magnetic field makes the clumps much more filamentary and that the filament axis tends to be aligned with the strain, i.e. the direction along which the fluid particles are stretched by the velocity field. This suggests that indeed turbulence, and even more likely, MHD turbulence naturally produces elongated structures. The role of the magnetic field is likely important because it makes the flow more coherent therefore allowing the existing filaments to survive longer. In a related way, the flows tend also to be more organized when magnetized. For example, several studies have concluded that velocity and magnetic field are preferentially aligned (see for example Iffrig & Hennebelle 2017). This is also consistent with the recent finding that the magnetic field direction and the density gradients are clearly correlated (Soler et al. 2013; Koch et al. 2013, 2014; Planck Collaboration et al. 2016; Soler & Hennebelle 2017). More precisely, it has been inferred that at low column density magnetic field tends to be orthogonal to the density gradients while it tends to be parallel to them at high column densities. This transition has been observed to occur in numerical simulations where the magnetic field is important and dominates over the thermal pressure (Soler et al. 2013).

3.2. A characteristic width?

Perhaps the most intriguing and recent aspect of filaments is the possible existence of a characteristic width and even more surprising is the fact that this remains true for filaments of column densities spanning almost 3 orders of magnitude (André et al. 2014). Indeed both gravity and turbulence tend to be scale free processes and usually produce powerlaws. For example the Jeans length varies by more than one of order of magnitude in the above mentioned filament sample.

Various explanations (André et al. 2014) have been put forward to account for this fact and entail self-gravitating equilibrium (Smith et al. 2014), the sonic length (Federrath 2015), the ion-neutral friction (Ntormousi et al. 2016) or the accretion (Hennebelle & André 2013; Gómez & Vázquez-Semadeni 2014). While some of them succeed to explain the observed width in some specific range of column density, none of the existing simulations has reproduced the characteristic width over 3 orders of magnitude in column density.

The problem is possibly less severe since a possible bias due to finite resolution has recently be claimed by Panopoulou et al. (2017). This may certainly account for some of the observed filaments in particular the low column density ones that are not as prominent as the very dense ones. The latter in particular are surrounded by an extended r^{-2} envelope which has not been considered in the bias analysis of Panopoulou et al. (2017). Note that it is quite possible that this bias may also be present in the analysis of some of the numerical simulations.

3.3. Fragmentation and core formation

In light of the recent Herschel results, several studies aiming at understanding the fragmentation of filaments in cores have been carried out. Clarke et al. (2016) performed a series of numerical simulations to study the fragmentation of a filament that is accreting (and not at equilibrium as assumed in previous studies). They find that due to the gravo-acoustic modes generated during the early phase of accretion, the dispersion relation depends on the accretion rate. Since the core spacing corresponds to the fastest growing mode, they propose a way to estimate the accretion rate of the observed filaments by measuring the core spacing. Gritschneder et al. (2017) performed simulations to understand the response of a marginally stable filaments to bending modes. These modes, which tend to make the filament oscillates perpendicularly to its main axis, trigger fragmentation and the formed cores have a spacing that matches the wavelength of the sinusoidal perturbation they used to generate the bending modes. This indicates that identifying characteristic spacing in filaments and relating them to filament properties should be handle with care.

The non-linear regime has been investigated numerically by Clarke et al. (2017). They carried out simulations where turbulence is seeded in accreting filaments and show that this generates fibers somehow similar to the ones that have been observed in Taurus (Hacar et al. 2013). It is argued that these fibers may play a role in preventing the radial collapse formed within super-critical filaments. Lee et al. (2017) have recently proposed an analytical theory to predict the core mass function (CMF) of supercritical filaments. The theory, which generalises the calculations performed by Hennebelle & Chabrier (2008), considers magnetized filaments assumed to be radially supported by turbulent motions. It predicts the CMF, which is found to depend on the mass per unit lengths (MpL) and the magnetic intensity. In particular, it is found that in the absence of magnetic field, filaments with high MpL fragment in too many small cores. In the presence of magnetic field with moderate intensities, CMF compatible with observed ones are inferred.

In the context of colliding flows, Gong & Ostriker (2015) carried out a series of numerical simulations and performing core extraction, also obtained realistic CMF.

4. Clusters

It is believed that stars do not form in isolation but rather in clusters. Indeed, observation ally stars do not form in the bulk of molecular clouds but instead in their denser parts. Large surveys have recently revealed ensemble of massive clumps in which stars are actively forming (Fall et al. 2010; urquhart et al. 2014; Traficante et al. 2015). These clumps have masses up to several thousands of solar masses and are very good candidates for being stellar cluster progenitors. Therefore studying their statistical properties may be an important clue to understand how clusters form. In particular, it has been found that these massive star forming clumps, follow a mass-size relation given by $M \propto R^{\gamma}$, where $\gamma \simeq 1.7$ or so. The typical clump radius varies between 0.1 and a few pc.

4.1. Formation and mass-size relation

The mass-size relation is particularly important because it provides the typical density of the massive star forming clumps and, most likely, traces the physical process responsible of the clump formation mechanism. In fact, Pfalzner et al. (2016) studied nearby clusters and concluded that the stellar clusters follow a similar mass-size relation, therefore seemingly suggesting that the cluster properties could be inherited from the parent clump characteristics.

Lee & Hennebelle (2016a) performed a series of simulations starting from a 10^4 $M_\odot$ collapsing clumps with various levels of turbulence. Using sink particles, they easily identified the regions where most stars formed. They then show that this broadly corresponds to a region of the cloud where virial equilibrium is nearly established. The incoming accretion flow is driving turbulence and the turbulent dispersion as well the clump rotation compensate for gravity. Analytical modeling (Lee & Hennebelle 2016b), that takes into account bidimensional virial equilibrium and energy balance, has been developed in parallel and compare well with simulations and observations. In particular the mass-size relation mentioned above is nicely reproduced.

Another explanation of the mass-size relation has been proposed by Li (2017) who constructed it by combining the virialised velocity field condition with the Kolmogorov cascade assuming that the energy flux through the cascade is the same for all structures.

4.2. Feedback processes

Significant efforts have been undertaken to model the feedback processes in clusters. The main goal is to infer an efficiency, that is to say the fraction of the mass, which is eventually converted into stars before the gas is expelled from the clusters. Typical estimates may indicate efficiencies of the order of 10-20 % (Pfalzner et al. 2016). It must be stressed however that the exact cluster boundaries are difficult to establish both for the gaseous and the stellar components. In particular, Lee & Hennebelle (2016a) inferred that both radii, while broadly related, do not exactly match, possibly leading to apparent efficiencies that should not be interpreted as a stellar to gas mass ratio.

In most clusters, the most important feedback mechanisms are expected to be the protostellar jets, the ionizing radiation and possibly the stellar winds. Supernovae for example are likely coming too late, since the most massive star lifetime is at least 4 Myr.

The role of the protostellar jets and outflows has been considered by Li et al. (2010); Wang et al. (2010); Federrath et al. (2014). In particular, it has been inferred that jets, together with turbulence and magnetic field, can reduce the star formation rate making it compatible with observed values. The role of the jets on the star formation efficiency, that is to say the total amount of gas converted into stars is less studied. However, since it is generally considered that only 10-30% of the accreted material is finally ejected in the jets and the outflows, entraining outside the clusters several time the accreted mass, seems unlikely.

The role of the ionizing radiation has been investigated in a series of papers by Dale et al. (2011, 2012, 2013); Walch et al. (2012); Walch & Naab (2015); Geen et al. (2015, 2016, 2017). Typically the influence of either a specified and unique UV source, either a self-consistent distribution of sources, on a prescribed turbulent molecular clouds is studied. It has been found that HII feedback can possibly limit significantly star formation in a cloud because the ionized gas has a sound speed of about 5-10 km s^{-1} and tends to expand, unbinding large amounts of gas. This however happens only if the cloud is not too bound. Dale et al. (2013) argued that the escape velocity should be smaller than the ionized gas sound speed, for HII to be efficient. Geen et al. (2017) compared the density PDF of the simulated clouds to the clouds from solar neighbourhood and found that for these latter the expected efficiency due to HII radiation is on the order of 20% while in the absence of ionizing feedback the efficiency is nearly 100%. For clouds several times denser, however, the efficiency is very high and almost equal to 100%. Note that strictly speaking, these efficiencies apply to the scale of the molecular clouds rather than the cluster ones. The impact on the clusters themselves has been investigated by Gavagnin et al. (2017) who concluded that ionizing feedback substantially modifies the internal structure of clusters making them less bound and the stellar densities less high. This likely has consequences on their evolution in particular because this causes less close encounters and reduces cluster evaporation.

Finally, radiative pressure could play an important role for the most massive clusters (Kim et al. 2016) and produce a radiation-driven explosion that may limit the efficiency of these clusters to about 50%.

5. ISM self-regulated models

Important efforts have also been undertaken to self-consistently simulate the interstellar medium within galaxies. Because modelling galaxies as a whole is very challenging in terms of scales, many models consider a computational box of about 1 kpc sometimes called galactic box. Since the typical supernova remnant radius is about 50 pc, this constitutes a good compromise between spatial resolution and molecular cloud statistics (though at the expense of solving the large galactic scales). The most recent models consider an external vertical gravitational field, which represents the gravity of stars and dark matter, follow the star formation (up to spatial scales of about 1-4 pc) and deliver stellar feedback (due to massive stars and essentially though not exclusively supernovae). This leads to a self-regulated ISM in which a turbulent cascade takes place. The energy is injected at the large and intermediate (around or above 100 pc) scales and decay at the small ones.

5.1. Star formation rate and vertical equilibrium

Recent studies (Hennebelle & Iffrig 2014; Gatto et al. 2015) have stressed the importance of the spatial and temporal correlations between the supernova remnants and the star forming dense gas. When the supernovae are randomly driven in the bulk of the galaxy, supernova feedback is inefficient and does not reduce the star formation rate, which is therefore far too high. On the other hand, when the supernova explosions correlate sufficiently with the dense gas, star formation rates compatible with the observed values are inferred (Kim et al. 2013; Hennebelle & Iffrig 2014; Iffrig & Hennebelle 2017). Noticeably, the thickness of the galactic disk formed in these simulations, is also compatible with the observed values while it is too narrow in simulations which drive the supernovae randomly. Cosmic rays may help in this as recently stressed by Girichidis et al. (2016). Getting a realistic mechanical equilibrium along the galactic disk axis is therefore essential. These models are also successful in reproducing a realistic multi-phase magnetized ISM with densities and temperature typical of the warm and cold neutral phase. The hot coronal gas is reproduced when the supernova forcing is done through energy injection but often the choice of injecting momentum instead is made as this makes the simulations less computationally expensive. When a magnetic field of a few μG is initially present in the simulations, the magnetic intensities stay compatible with the observed values. One drawback of these models is that the feedback is injected immediately, while supernovae in particular arise 4-40 Myr after the formation of their progenitors. Since the typical freefall time of a dense star forming cloud is a few Myr, this is an important effect to take into account. The most advanced models (Kim & Ostriker 2016) are now doing it more self-consistently. It should be stressed however that the only way to treat the feedback injection properly is to solve the star formation and evolution self-consistently. This would ideally require to resolve much smaller spatial scales that what is currently possible for this type of modelling.

5.2. Turbulence and clumps

Due to the small timesteps induced by the large velocities and temperatures generated by supernova remnants, this type of calculations is quite demanding and only moderate spatial resolutions are usually used. Iffrig & Hennebelle (2017) have recently performed a set of 1024^3 runs which allow to study the properties of turbulence and the statistics of structures. In spite of the multi-phase nature of the flow and the very prominent stratification, the various powerspectra are broadly compatible with earlier works (see e.g. Hennebelle & Falgarone 2012) though the velocity powerspectrum is closer to the classical Kolmogorov exponent than the stiffer, almost Burgers like, values inferred in supersonic isothermal turbulence. Interestingly, the ratio of the energies of the compressible modes and solenoidal ones strongly varies with altitude. In the midplane, the compressible modes dominate while above a certain altitude, which depends on the magnetic intensity, the solenoidal ones dominate. This result differs from the conclusion of Padoan et al. (2016) who found that the solenoidal modes always dominate. The discrepancy may come from the difference in the supernova schemes adopted in both studies or to the absence of stratification in Padoan et al. (2016). Using a simple clump finder, the dense clouds have been extracted from the simulations of Iffrig & Hennebelle (2017) and Padoan et al. (2016). Their statistical properties such as the mass spectra, the mass-size and the internal velocity dispersion-size relations are all reminiscent of the observed cloud properties (e.g. Miville-Deschênes et al. 2017) though Iffrig & Hennebelle (2017) mentioned that the internal velocity dispersions are possibly smaller than observed clouds. This may indicate the need for other energy injection sources such as the injection through large galactic scale gravitational instabilities (Krumholz & Burkhart 2016).

5.3. Chemistry

Some efforts have also been dedicated to the treatment of chemistry within large scale numerical simulations, both to understand the fundamental processes and to improve the comparison with observational tracers such as the CO molecule. Considering turbulent molecular clouds of 10^4-10^5 $M_\odot$, Clark & Glover (2015) found, using a chemical network and performing radiative transfer, that the X_{CO} factor, i.e. the conversion factor between integrated CO emission and the column density of hydrogen, may vary by a factor 2 to 10 when the UV field is changed by 2 orders of magnitude. Using the colliding flow set-up, Valdivia et al. (2016) have simulated the formation of the H_2 molecule. They stress that due to the turbulence mixing and the multi-phase nature of molecular clouds, a few percents of warm dihydrogen, that is to say having temperature above $\simeq$ 500 K, are rapidly created. This leads to a population of rotationally excited molecules and the column densities of the various levels are compatible with observations. In a second step, Valdivia et al. (2017) computed the abundances of other molecules such as CH_+ and show that the latter can be efficiently produced, in spite of its high activation barrier, due to the presence of warm H_2. Therefore the existence of the rotationally excited molecules and of molecules such as CH_+ may probe the multi-phase nature of molecular clouds. Walch et al. (2015) discussed the formation of H_2 in the context of galactic box and showed in particular that H_2 abundance is very sensitive to the supernova scheme used in the simulations.

6. Conclusions

Significant progress has been accomplished in the last years. We have a better, although still incomplete, understanding on the structures, filaments, cores, clumps, clusters, formation mechanisms. Most likely they are all the product of magnetized turbulence interacting with gravity. One important difficulty, however, is their definitions both in observations and in simulations. Indeed, it is almost never the case that a structure is completely detached from the surrounding environment. Clearly finding new ways to quantify structures and to compare observations and simulations would be a source of major progress. Much efforts have been devoted to the understanding of the feedback processes. While it seems to be clear that they are essential in setting both the star formation rate within galaxies and the star formation efficiency within molecular clouds and that broad agreement with observed values can be obtained, a clear quantitative estimate of the model accuracy is required. The multi-scale nature of star formation as well as the use of recipes to treat feedback and to follow stars make such an effort a real necessity. A major challenge for the field of star formation is to get a reliable and complete description of the life cycle of molecular clouds from their birth, out of an HI envelope, to their end, likely dispersed by the internal stellar feedback.

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