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Statistical mechanics of non-extensive systems/Mécanique statistique des systèmes non-extensifs

The turbulent interstellar medium

Andreas Burkert

University Observatory Munich, Scheinerstr. 1, 81679 Munich, Germany

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Abstract

An overview is presented of the main properties of the interstellar medium. Evidence is summarized that the interstellar medium is highly turbulent, driven on different length scales by various energetic processes. Large-scale turbulence determines the formation of structures like filaments and shells in the diffuse interstellar medium. It also regulates the formation of dense, cold molecular clouds. Molecular clouds are now believed to be transient objects that form on timescales of order 10^7 yrs in regions where HI gas is compressed and cools. Supersonic turbulence in the compressed HI slab is generated by a combination of hydrodynamical instabilities, coupled with cooling. Turbulent dissipation is compensated by the kinetic energy input of the inflow. Molecular hydrogen eventually forms when the surface density in the slab reaches a threshold value of $\sim 10^{21}\ \mathrm{cm}^{-2}$ at which point further cooling triggers the onset of star formation by gravitational collapse. A few Myrs later, the newly formed stars and resulting supernovae will disperse their molecular surrounding and generate new expanding shells that drive again turbulence in the diffuse gas and trigger the formation of a next generation of cold clouds. Although a consistent scenario of interstellar medium dynamics and star formation is emerging many details are still unclear and require more detailed work on microphysical processes as well as a better understanding of supersonic, compressible turbulence. ***To cite this article: A. Burkert, C. R. Physique 7 (2006).***

Résumé

Le milieu interstellaire turbulent. Les propriétés principales du milieu interstellaire sont présentées. Les preuves sont réunies pour montrer que le milieu interstellaire est hautement turbulent, et que l'énergie lui est fournie à différentes échelles par divers processus. La turbulence à grande échelle détermine la formation des structures, comme les filaments et coquilles du milieu interstellaire diffus. Elle régule aussi la formation des nuages moléculaires froids et denses. Les nuages moléculaires sont considérés aujourd'hui comme des objets transitoires qui se forment sur des échelles de temps de 10^7 ans, dans des régions où le gaz HI est comprimé et se refroidit. La turbulence supersonique dans la couche HI comprimée est engendrée par une combinaison d'instabilités hydrodynamiques et de refroidissement. La dissipation turbulente est compensée par l'apport d'énergie cinétique du flux de gaz. Enfin l'hydrogène moléculaire se forme, lorsque la densité de surface dans la couche atteint le seuil de $\sim 10^{21}\ \mathrm{cm}^{-2}$; alors le refroidissement déclenche la formation d'étoiles par effondrement gravitationnel. Quelques millions d'années plus tard, les nouvelles étoiles formées et les explosions de supernovae qui en résultent dispersent le milieu moléculaire environnant, et engendrent de nouvelles bulles en expansion, qui à nouveau créent de la turbulence dans le gaz diffus, et déclenchent la formation d'une nouvelle génération de nuages froids. Bien qu'un scénario cohérent de la dynamique du milieu interstellaire et de la formation d'étoiles émerge, bien des détails sont encore obscurs, et demandent plus de travail sur les processus microphysiques, et aussi une meilleure compréhension de la turbulence supersonique et compressible.***Pour citer cet article : A. Burkert, C. R. Physique 7 (2006).***

E-mail address: burkert@usm.uni-muenchen.de (A. Burkert).

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Mots-clés : Milieu interstellaire ; Turbulence ; Nuages moléculaires ; Formation d'étoiles ; Galaxies

1. Introduction

Steady-state multi-phase models have dominated our picture of the interstellar medium (ISM) in the Milky Way for a long time. According to the early model of Field et al. [1] and subsequent modifications, the ISM represents an ensemble of two stable gas phases that are in thermal pressure equilibrium with a mean pressure of $n \times T \approx 1000\ \mathrm{K/cm^3}$. Cold molecular clouds with mean densities of $n \approx 100\ \mathrm{cm^{-3}}$ and temperatures $T \approx 10$ K are embedded in a warm, diffuse and partly ionized intercloud component with density $n \approx 0.1\ \mathrm{cm^{-3}}$ and temperatures of order 10^4 K. The gas clouds contain a large fraction of the total mass and move as stable, dense spheroidal objects in the widespread intercloud medium which on the other hand has the dominant volume filling factor. Star formation would eventually heat and disperse the massive clouds. New generations of small clouds form from the intercloud medium by cooling instabilities (Field [2]) and subsequently grow by random inelastic cloud–cloud collisions (e.g., Elmegreen [3]). Already in 1977 McKee and Ostriker [4] noticed that the two-phase model could not be valid as supernova explosions should lead to a third, hot and tenuous gas phase. However, they still focussed on the importance of thermal pressure equilibrium and a steady state description as the main physical constraint to evaluate the state of the various gas phases.

This situation has changed drastically in the last decade. High-resolution observations, e.g., with the Infrared Astronomical Satellite (IRAS) and more recently with the Spitzer satellite reveal a complex kinematical state and spatial structure of the interstellar gas. The ISM appears to be far from hydrostatic equilibrium and turbulent. In fact, it is the kinetic turbulent pressure, not thermal pressure, that probably dominates the gas dynamics and that characterizes its density structure and the dynamics of the various gas phases. Turbulence couples structures on very different scales. Molecular clouds might just represent the high-density tail of this hierarchy, forming in colliding gas flows that lead to transient local compressions that subsequently cool. We will discuss below that the complex internal structure of molecular clouds that determines their evolution and their condensation into stars and stellar clusters is also a result of turbulence, generated by various hydrodynamical instabilities during the process of molecular cloud formation.

With turbulence becoming the dominant source of structure in the ISM, theoretical models lost their simplicity and equilibrium descriptions had to be replaced by dynamical models where large and small scales are simultaneously considered. We are just starting to explore and understand this rich and enormously complex new field of astrophysics. In this short review I can only focus on a few interesting topics and unsolved questions. An excellent and comprehensive review of our current understanding is presented by Elmegreen and Scalo [5], and Scalo and Elmegreen [6]. Reviews that focus especially on numerical simulations of ISM turbulence are, e.g., Vázquez-Semadeni et al. [7] and Ballesteros-Paredes et al. [8]. A summary of our understanding of star formation in turbulent clouds is given by Mac Low and Klessen [9].

2. Turbulence in the diffuse ISM

It is now a well-established fact that the ISM in galactic disks is dominated by irregular and often supersonic gas motions (Larson [11]; Scalo [12]; Dickey and Lockman [13]). In most spiral galaxies HI emission lines exceed the values, expected from thermal broadening, indicating turbulent velocity dispersions σ of order 10 km/s. The velocity dispersion in galactic disks in general decreases outwards from $\sigma \approx 12$–15 km/s in the inner regions to $\sigma \approx 4$–6 km/s in the outer parts. Fig. 1 shows the characteristic velocity dispersion for a sample of galaxies as function of their surface averaged star formation rate (Dib et al. [10]). Note that self-regulated star formation rates that are typical for Milky Way-type disk galaxies lead to velocity dispersions of order $\sigma \approx 6$–8 km/s, independent of the star formation rate. The diffuse ISM acts like a thermostat. The situation changes drastically in situations where star formation is getting out of control, leading to starbursts that last a short time, of order 10^8 yrs. As shown in Fig. 1, the transition into the starburst regime is marked by a steep increase of the velocity dispersion.

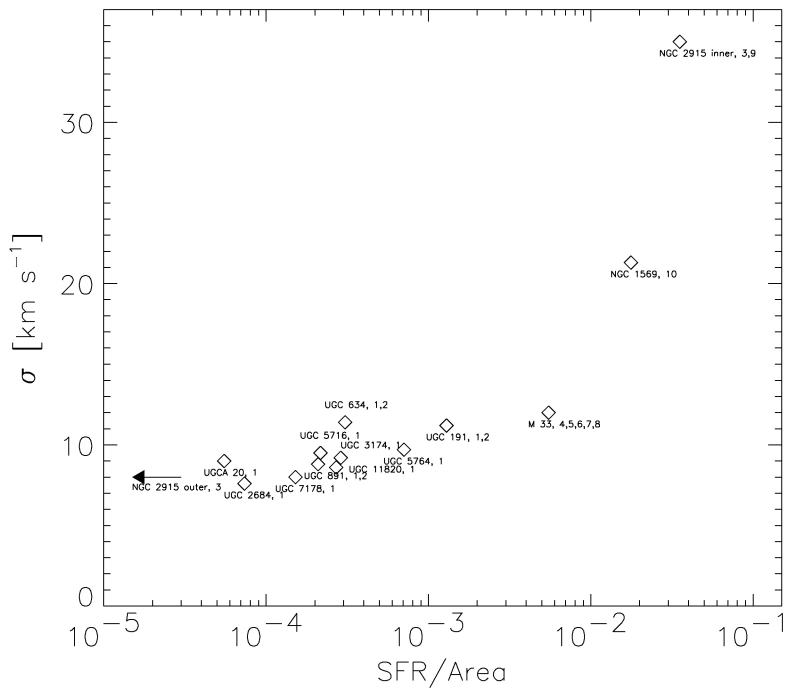

Fig. 1. Characteristic velocity dispersion σ of a sample of disk galaxies as function of their average surface star formation rate in units of ($M_\odot\ yr^{-1}\ kpc^{-2}$) (Dib et al. [10]). σ is almost independent of the star formation rate for typical values found in slowly evolving disk galaxies like the Milky Way. It rises steeply in starburst regions with high star formation rates.

2.1. Driving turbulence in the diffuse ISM

Several physical processes, acting on different scales and injecting different amounts of kinetic energy contribute to the driving of ISM turbulence. However, despite a large amount of numerical work in this field, the dominant energetic sources and the physical processes that convert the kinetic energy into turbulence are not well understood. Stars are obvious candidates. Large-scale expanding gas flows could, e.g., be generated by high-pressure HII regions, resulting from the UV radiation of young, massive stars (Kessel-Deynet and Burkert [14]), stellar winds or supernova explosions. Mac Low and Klessen [9] argue that supernova explosions dominate the global kinetic energy input into the interstellar medium. Several two- and three-dimensional numerical simulations have tested supernova driving in galactic disks (e.g., Kim et al. [15]; de Avillez and Breitschwerdt [16,17]; Slyz et al. [18]; Mac Low et al. [19]). The recent investigation by Dib et al. [10] demonstrates that the HI gas velocity dispersion saturates at values of 3 km/s for values of the supernova rate, ranging from 0.01 to 0.5 the Galactic value ($1/57\ yr^{-1}$, Cappellaro et al. [20]). It increases sharply at larger rates, reproducing the transition into the starburst regime. Although the constant velocity dispersion, found at lower rates is promising, the actual value of 3 km/s is a factor of 2–3 lower than observed. Part of this discrepancy might be due to thermal line broadening. However, other feedback processes probably are also important to produce the observed level of turbulence in galactic disks.

What is the origin of a constant HI velocity dispersion, independent of the supernova rate? Dib et al. [10] argue that the answer lies in a dominant gas phase that is in a thermally unstable temperature regime between $400\ K \leqslant T \leqslant 10\,000\ K$. It is produced when individual supernova remnants cool and are dispersed. In these regions thermal instability (Burkert and Lin [21]) generates local irregular pressure gradients that lead to HI gas flows with typical velocities of order the local sound speed, corresponding to a few km/s. The importance of thermal instability as a driver of turbulence in the ISM has previously been discussed in details by Kritsuk and Norman [22,23]). In the starburst regime, on the other hand, supernova remnants begin to overlap in an early hot phase, generating a stable, hot gas component with a large volume filling factor. HI flows are now directly coupled to the expansion of bubbles generated by multiple supernovae, leading to larger velocities that are however still subsonic with respect to the hot gas component.

Note that in the Milky Way this scenario would predict the existence of a thermally unstable gas phase with a high mass fraction (Gazol et al. [24]), in contrast to previous static multi-phase models. A large fraction of interstellar gas in the unstable regime has indeed been observed (Dickey et al. [25]; Heiles [26]; Kanekar et al. [27]). As outlined by Elmegreen and Scalo [5], this phase also explains the origin of large variations in observed gas pressures that were puzzling in the static models (Jenkins [28]; Kim et al. [15]).

Many physical mechanisms, not related to stellar energetic feedback, could in principle contribute to the driving of turbulence in the ISM. Clear evidence for additional sources is for example the high HI velocity dispersion observed in the outer parts of galactic disks where star formation is negligible (Dickey et al. [13]). Numerical simulations are just starting to explore these drivers of turbulence in greater details. Galactic rotation, for example, represents a huge reservoir of kinetic energy. Wada et al. [29] demonstrate that the dissipation of turbulent energy in disks could be compensated by a combination of galactic shear and gas self-gravity. In addition, the coupling of galactic shear with magnetic fields can trigger a magnetorotational instability (MRI) (Balbus and Hawley [30]; Sellwood and Balbus [31]). Three-dimensional simulations by Kim et al. [32] show that the MRI could generate velocity dispersions of order a few km/s which is similar to supernova driving (see also Dziourkevitch et al. [33]). Similar values are found by Piontek and Ostriker [34] who studied the combined affect of thermal instability and MRI.

Only recently have galaxies in early phases of evolution been detected in deep images with the Hubble Space Telescope (e.g., Cowie et al. [35]; Tran et al. [36]; Elmegreen et al. [37], Forster Schreiber et al. [38]). They are characterised by a few giant blue, bright clumps of sizes ∼500 pc where stars appear to form with high efficiency in a starburst mode. The clumps dominate the disk light, suggesting a global gravitational disk instability and implying an unusually high velocity dispersion of order 30% the disk rotational velocity (Elmegreen [39]), corresponding to 40–60 km/s which is similar to the velocity dispersion of the thick disk component of the Milky Way. The triggering mechanism of this highly turbulent starburst mode in young galaxies and its affect on the evolution of the various galactic components and galaxy morphologies is not well understood up to now.

2.2. HI holes and the complex filamentary structure of the ISM

The left panel of Fig. 2 shows the peak 21 cm HI surface density distribution in the Large Magellanic Cloud (Kim et al. [40]) which reveals a complex network of interacting filaments, shells and superbubbles. The question of which physical processes produce these holes in the LMC and other galaxies is not solved. Their circular shapes suggest

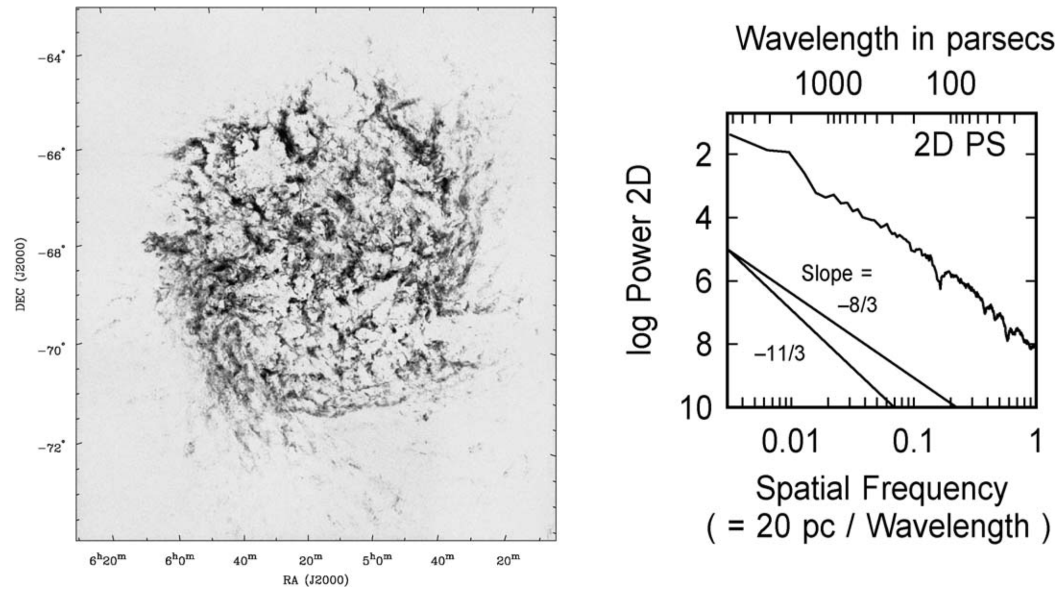

Fig. 2. The left figure, provided by S. Kim (Kim et al. [40]), shows the peak 21 cm HI surface density distribution in the Large Magellanic Cloud which nicely demonstrates the existence of a complex network of filaments and shells. The right figure, provided by B. Elmegreen (Elmegreen et al. [41]), shows the power spectrum of the HI emission in the LMC which is well fitted by a power-law of slope −3 over 2 decades in length.

a stellar central energy source. Observations however indicate that the voids especially in the outer parts of galactic disks are often not a result of supernova explosions. Kim et al. [40] for example find only a weak correlation between the positions of the HI shells in the LMC and HII regions. Rhode et al. [42] have studied 51 HI holes in the dwarf galaxy Holmberg II (Puche et al. [43]). They show that in 86% of all cases the holes do not show any signature of the presence of an embedded stellar cluster or any sign of ongoing stellar activity. In fact, X-ray observations of Holmberg II show that the HI holes are often devoid of hot gas (Kerp et al. [44]) and therefore probably did not form by the expansion of a hot gas bubble, sweeping up its environment.

Dib and Burkert [45] suggest that large HI holes can form naturally as a combined result of ISM turbulence, coupled with thermal and gravitational instabilities. Their hydrodynamical simulations of large-scale driven turbulence, including cooling and heating processes as well as self-gravity can reproduce the structure of shells and holes, observed in regions where no stellar activity is observed. For a more quantitative analyses they subdivided the gas disk into rectangular cells of constant size l and determined the autocorrelation lengthscale of the HI surface density distribution in each cell. Averaging over all cells, the mean autocorrelation length scale $l_{\rm cr}$ was determined as function of cell size l. Dib and Burkert find that $l_{\rm cr}$ increases linearly with l as long as the cell size is smaller than the length scale $l_{\rm turb}$ on which turbulent energy is injected into the ISM. Once $l > l_{\rm turb}$, the autocorrelation lengthscale becomes independent of the map size. This analysis can be used to determine the scale of energy injection into the ISM for observed HI disks. Applying the method to Holmberg II leads to a driving scale of $l_{\rm turb} \approx 6$ kpc which is very puzzling as this scale is much larger than any known energy source in the galaxy.

The power spectra of 2D gas column densities and emission fluctuations are often fitted well by power-law profiles with a slope around -3 (right panel of Fig. 2, see Elmegreen et al. [41]). This power-law extends from the largest to the smallest observable scales which is surprising given the fact that multiple sources of energy are likely to contribute to the driving of turbulence on very different length scales. The similarity of this slope to a 2D Kolmogorov power spectrum (Kolmogorov [46]) of $-8/3$ is also not well understood as Kolmogorov's scaling relations are strictly valid only for incompressible fluids where vortices (solenoidal modes) are the relevant dynamical structures in contrast to the ISM where compressible modes leading to shocks and rarefaction waves are important. As the Fourier transform of a step function has a 2D power-law slope of -3 (Mac Low and Klessen [9]) we might just see the complex network of interacting shock fronts. Unfortunately numerical simulations of the turbulent supersonic ISM do not have enough dynamical range yet to investigate this interesting question in greater details.

3. Turbulence in the dense, cold interstellar medium

Stars form in the cold, dense molecular phase of the interstellar medium where clumps with masses in the stellar regime can become gravitationally unstable and collapse. Like the diffuse ISM, molecular clouds (MC) exhibit a wealth of clumpy and filamentary substructures that indicate that they are again turbulent regions, embedded and interacting with the turbulent diffuse interstellar medium.

3.1. The problem of star formation in a crossing time

How stars form in MC is an important unsolved question of modern astrophysics (for a review see Mac Low and Klessen [9]). Ordinary spiral galaxies like the Milky Way form stars at a low, self-regulated rate. Although a large fraction of the visible gas is condensed in MCs with masses in the range of 10^4–10^6 $M_\odot$ that by far exceed their thermal Jeans mass, star formation turns out to be surprisingly inefficient (Blitz and Shu [50]). The Milky Way, for example, with a total molecular gas mass of order 2×10^9 $M_\odot$ and mean molecular cloud densities of order 100 cm^{-3}, corresponding to collapse timescales of 5×10^6 yrs, could in principle form stars with a rate of more than 100 $M_\odot$/yr which is a factor of 100 larger than observed.

Supersonic (Mach numbers: $M \approx 5$–10) turbulent gas motions have been detected in most cloud complexes (Larson [11], Falgarone and Philips [51]; Elmegreen and Falgarone [52], Williams et al. [53]) and are considered as the main source for their stability and complex density structure. However numerical hydro- and magneto-hydrodynamical simulations show that supersonic turbulence dissipates on timescales shorter than the collapse timescale (Stone et al. [54]; Mac Low et al. [55]). In addition, no driver of molecular cloud turbulence has ever been found which on the one hand suppresses star formation on the small scales while, at the same time, stabilizing giant molecular clouds on the large scales (Heitsch et al. [56]).

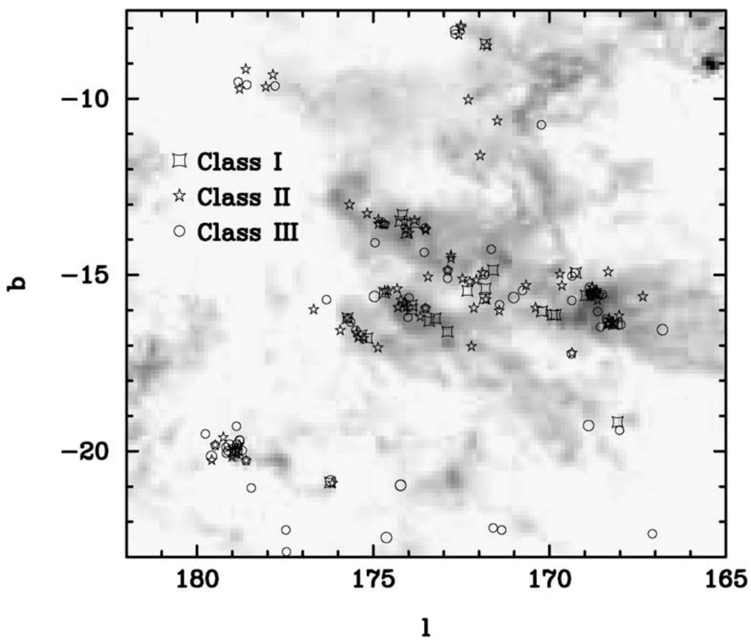

Fig. 3. The distribution of young stars in the Taurus molecular cloud, superimposed upon ^{12}CO emission. Most of the stars have ages of order 2 Myr despite the fact that the lateral sound crossing time is of order 20 Myr (figure provided by L. Hartmann; see Hartmann et al. [47] and Hartmann [48,49]).

Another serious problem is the so-called post-T Tauri problem (Hartmann [57,48,49]; Hartmann et al. [47]): the typical age spread of young stellar populations is of the order of 1–3 Myrs which is surprisingly narrow, indicating a coherent star formation process (see, however, Palla et al. [58]). Fig. 3, for example, shows the young stars observed in the Taurus complex. They are aligned in 3 parallel filaments at the ridges of an irregular diffuse gas complex. The origin of this alignment is not understood. In addition, the age spread of the stars is only a few Myrs which is a factor of 10 smaller than the lateral sound crossing times of the filaments. Which processes triggered star formation coherently along all three filaments at exactly the same time? Finally, almost all molecular clouds in the solar neighborhood show signs of star formation which implies that they cannot be much older than a few Myrs as otherwise either the newly formed stellar systems should have a larger age spread or a larger fraction of clouds should not show signatures of star formation.

If molecular clouds condense into stars within a few Myrs the problem arises how clouds with masses of 10^3–10^6 $M_\odot$ could form in the first place. Consider a perturbation travelling through the ISM and sweeping up gas. Adopting typical velocities of order 10 km/s, cross sections of order $(10\ \mathrm{pc})^2$ and densities of the diffuse gas that is being swept up of order 1 cm^{-3} it takes more than 10^7 yrs to accumulate a total mass of 10^3–10^4 $M_\odot$. Giant molecular clouds might form in larger-scale spiral arms with dimensions of several 100 pc and speeds of order 50–100 km/s (Bonnell et al. [59]). Still, several 10^7 yrs are required which is in conflict with the above mentioned molecular cloud lifetimes.

3.2. Formation of molecular clouds in converging gas flows

The arguments, presented in the previous section, indicate that molecular cloud formation and evolution is highly dynamical and that clouds never have the time to achieve a long-term equilibrium state, supported by internal turbulence. They instead form from the turbulent diffuse ISM with their irregular motions and filamentary substructures probably already imprinted at the time of formation. They are dispersed a few dynamical timescales later by star formation. That molecular clouds are transient dense islands in a turbulent sea and part of a hierarchy of structures that form in the ubiquitous colliding shock waves of the turbulent, diffuse ISM has already been outlined a long time ago by von Weizsäcker [60], (for a summary of early work in this field see Elmegreen and Scalo [5]). At that time however it was not possible to study this model with numerical methods in details.

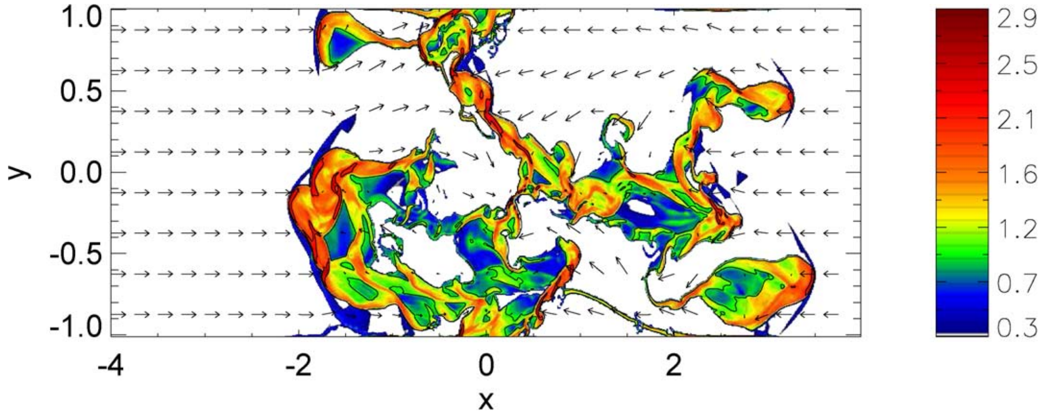

Fig. 4. Formation of a turbulent, irregular dense sheet of cold gas in the interaction zone of two colliding gas flows with inflow velocity of 10 km/s and temperature of 3000 K. The density distribution of the cold gas with a temperature of $\leqslant$300 K is shown. The colorbar shows the logarithm of the particle density in units of cm^{-3}. Vectors show the velocity of the diffuse intercloud medium that moves into the inner region of the cold gas complex along open channels, driving irregular turbulent flows in its interior.

The situation has changed in the meantime due to sophisticated numerical schemes and the availability of fast computers. The cooling and subfragmentation of dense slabs that form in colliding gas flows has now been investigated in details (Walder and Folini [61,62]; Klein and Woods [63]; Heitsch et al. [64,65]; Vázquez-Semadeni et al. [66]; Bonnell et al. [59]). It has been shown that the compressed region fragments as a result of a combination of thermal- and hydrodynamical instabilities (non-linear thin shell instability: Vishniac [67]; Kelvin-Helmholtz instability: Blondin and Marks [68]: thermal instability: Burkert and Lin [21]; see also Hennebelle and Pérault [69,70]; Koyama and Inutsuka [71]). Fig. 4 shows an example of a fragmenting, cold compressed slab. Dense filamentary and clumpy HI substructures with temperatures of order 100 K are forming that move with irregular velocities in a diffuse interclump medium. The numerical simulations show that even with modest inflow speeds and completely uniform inflows, non-linear density perturbations form that could represent the seeds of structure in molecular clouds. These irregular sheets and filaments might lateron collapse and fragment into stars (e.g., Burkert and Bodenheimer [72]; Klessen and Burkert [73]; Burkert and Hartmann [74]). The random gas velocities within individual cold clumps are quite small. However the relative velocities of the cold gas clumps with respect to each other are highly supersonic, compared to the sound speed of the cold component and consistent with the observed values of a few km/s. The irregular, turbulent motion of the cold gas in the slab is continuously driven by the kinetic energy of the inflowing diffuse gas. This might stabilize the region against gravitational collapse as long as the inflow continues.

If the inflowing gas is preferentially HI, a dense irregular HI slab forms. The formation of molecular gas starts as soon as the HI surface density reaches values of $\Sigma_{\mathrm{crit}} \approx 10^{21}\ \mathrm{cm}^{-2}$ (Bergin et al. [75]). For inflow speeds of 10 km/s this will require timescales of order a few 10^7 yrs for densities of the inflowing material of 1 cm^{-3}. The accumulated molecular cloud mass would then be of order 1000 $M_{\odot}$ which is typical for filamentary molecular clouds like Taurus in the solar neighborhood. Similar timescales are required in the larger-scale flows in spiral density waves that produce giant molecular cloud complexes. During the early period of proto-cloud evolution, the gas would still be atomic and not easily detectable. Bergin et al. [75] show however that as soon as Σ_{crit} is reached, the conversion into a molecular cloud takes only a few 10^6 yrs. In addition, the previously 100 K gas would cool down to 10 K which could trigger local gravitational collapse and star formation. More work is required to detect this gas phase observationally and investigate its evolution with numerical simulations.

4. Summary

The interstellar medium is a highly turbulent mixture of various interacting gas phases. The existence of turbulence is expected, given the fact that the typical Reynolds numbers in the ISM are of order 10^4–10^7 (Elmegreen and Scalo [5]). That turbulence is however also found in regions without energy input by stars is surprising.

A wealth of connected and coupled structures on different scales all the way down to the scale of star formation have been identified, starting with the early work of Larson [11] who found that the density and velocity dispersion of molecular clouds scales with the size of the region as a power law. This indicates an interesting connection between ISM dynamics and star formation. Many questions are still unsolved and need to be explained theoretically. This might eventually lead to a quantitative model of star formation that is one of the crucial missing ingredients in order to understand the evolution of galaxies.

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