The interstellar medium: from molecules to star formation

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Resumen / El medio interestelar (MIE) es un medio extremadamente complejo que contiene toda la materia necesaria para la formación de estrellas y sistemas planetarios. El MIE se encuentra en permanente interacción con la radiación, turbulencia, campos magnéticos y gravitatorios, y partículas aceleradas. Todo lo que ocurre en este medio tiene consecuencias en la dinámica y evolución de la galaxia, resultando así ser el enlace que relaciona las escalas estelares con las galácticas. El estudio del MIE es entonces fundamental para avanzar de una manera integral en el conocimiento de la astrofísica estelar y galáctica. En este trabajo se presenta un resumen de lo que conocemos hoy en día sobre la física y química de este medio, haciendo especial énfasis en la formación de estrellas, y cómo éstas a través de los procesos relacionados a su nacimiento y evolución, se interrelacionan con el medio que las rodea y contiene.

Abstract / The interstellar medium (ISM) is a very complex medium which contains the matter needed to form stars and planets. The ISM is in permanent interaction with radiation, turbulence, magnetic and gravitational fields, and accelerated particles. Everything that happens in this medium has consequences on the dynamics and evolution of the Galaxy, resulting the link that relates the stellar scale with the galactic one. Thus, the study of the ISM is crucial to advance in the knowledge of stellar and galactic astrophysics. In this article I present a summary of what we know about the physics and chemistry of this medium, giving a special emphasis on star formation, and how the processes related to the stars birth and evolution interrelate with the environment that surrounds them.

Keywords / ISM: structure — ISM: kinematics and dynamics — ISM: molecules — stars: formation

1. Defining and classifying the interstellar medium

All in the Galaxy is embedded in the interstellar medium (ISM), which is a dynamic, ever-changing environment. We can say that the Galaxy, besides the dark matter, is composed by stars and regular matter distributed between them, which conforms a medium of low density. The ISM is not homogeneous, indeed it can have, from place to place, very different physical and chemical conditions according to the influence of the radiation, turbulence, magnetic fields, and cosmic rays. In that sense it is not possible to classify the ISM among well defined components, and thus, in the literature it is usually given schematic classifications, such as in Lequeux (2005) (see Table 1), or in Tielens (2005), between others.

Table 1 shows that all the ISM phases or components are extremely tenuous comparing with terrestrial environments. For instance, if we consider even the densest phase, i.e. the molecular phase, which can have densities from some $10^4$ to about $10^7$ cm$^{-3}$, this is several orders of magnitude less dense than, for example, the atmosphere of our planet that contains about $10^{19}$ molecules per cm$^3$.

The matter of the ISM represents about 5% of the total stellar mass in the Galaxy, and its composition is about 70% hydrogen, 28% helium, and 2% of heavy elements (Lequeux 2005). In turn, these elements can be neutral or ionized, and can be assambled into molecules.

From the total matter of the ISM, the fraction of atomic ionized matter is 23%, while the atomic neutral matter represents a 60%. Finally, the portion of molecular matter is about 17% (Draine 2011).

In spite of being a medium of low density and representing a small fraction of the total mass in the Galaxy, the ISM is extremely important for the galactic evolution. It contains all the matter to form new generations of stars and planets, and its molecular phase is composed by complex molecules, including pre-biotic ones. Thus, this article is focused on the molecular component of the ISM and the star formation processes that occur in it.

2. Molecules in the ISM

Although astronomical molecules are detected in diverse astrophysical environments, the molecular material in
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general, and the complex molecules in particular, are mainly associated with molecular clouds and their dense clumps, which comprises both a gaseous phase and a solid one of small dust particles. The analysis of the molecular spectra and the chemical chains of reactions that yield different molecular species are useful to probe the ISM components and the processes that occur in it. The molecular spectra gives physical information on the gas and dust. In particular, rotational and vibrational spectra tell us about the density and temperature of the gas as well as the kinematics of it, such as collapse and rotation (Herbst & van Dishoeck 2009).

The richness of the molecular component of the ISM is evidenced by the large number of known molecules. Up to date around 200 molecules have been detected in the ISM or circumstellar shells. For a quick revision of the known molecules I recommend to visit https://www.astro.uni-koeln.de/cdms/molecules from the University of Cologne, where it can be find an up to date list of molecules ordered by the number of atoms that compose them. Another interesting website where it is presented the known molecules ordered as chronologically as were discovered is: http://www.astrochymist.org/ism.html from the site http://www.astrochymist.org/, where there are much information and links about astrochemistry. As can be seen from these catalogues and from many works in the literature (see for example Ehrenfreund & Charnley 2000, Herbst & van Dishoeck 2009, Belloche et al. 2013, Bonfand et al. 2017), a large number of the known molecular species are complex and organic molecules.

2.1. Complex molecules: the role of the dust

Given to the low densities, the intense UV radiation and the constant flux of cosmic rays, the main chemical reactions in the ISM should be quite different than those that take place in our planet. Nowadays it is well established that the main chemical reactions in the ISM are the ion-molecule reactions, and the chemistry on the surface of the interstellar dust. The first one is part of the gas-phase chemistry, which also include others reactions such as radiative association, dissociative recombination, neutral-neutral reaction, and photodissociation and photoionization. For a review of these chemical processes, and their relative importance, see for example Lequeux & Roueff (1991), Herbst (1995), and Lequeux (2005). A more recent overview of astrochemistry with extensive reference lists can be found in Tielens (2013). Here, I focus on the role of the interstellar dust in the formation of complex molecules in dark clouds, the sites of star formation.

The interstellar dust is the main component of the ISM responsible for the visual extinction (Figure 1) and the study of its composition began about a century ago. For instance, Spitzer (1941) proposed, not so wrongly, the presence of metallic particles embedded in the clouds distributed in the galactic plane. Along the years much effort was done in order to explain the composition of this solid component. In this context, for example Gould & Salpeter (1963), following van de Hulst (1949), considered dust grains that consist of something like between a hydrogen-bonded crystal (ice) and a molecular crystal, while Stecher & Williams (1966) mentioned grains of pure-graphite. To mention a flamboyant case, Hoyle & Wickramasinghe (1979a,b) suggested that microbiological systems such as virus, bacteria, and algae could explain the interstellar extinction. Nowadays we know that the solid component of the ISM is composed by tiny solid particles of $\sim 0.01-0.5 \mu m$ in size consisting of silicates and carbonaceous material (Draine 2003, Draine & Li 2007), that in the cold dense clouds the gas-phase chemical species condense on them forming icy mantles (see Fig. 2 left).

![Figure 1: Beverly Lynds Dark Nebula 183. This is an example of the visual extinction due to the presence of interstellar dust. Image extracted from https://apod.nasa.gov/apod/ap171021.html; credit & copyright: Fabian Neyer.](image1)

![Figure 2: Left: Cartoon of a dust grain with an icy molecular mantle (image extracted from the cosmic-dust chapter in https://courses.lumenlearning.com/astronomy/). Right: Cartoon of the interaction of hydrogen atoms with a dust grain (image from Vidali (2013a)).](image2)

The interstellar dust is responsible of the formation of the most basic and abundant molecule in the Universe, the molecular hydrogen ($H_2$). Roughly, the
principle of \( \text{H}_2 \) formation is simple: two \( \text{H} \) atoms stick onto a dust grain, encounter one another and form the molecule (Hollenbach & Salpeter, 1971). This stickiness process can be due to physical and/or chemical adsorption (e.g. Vidali 2013b), which depend on the dust temperature, composition, and presence, or not, of a mantle. Once on the surface, the \( \text{H} \) atom can evaporate or hop across it until encountering another \( \text{H} \) atom and form the molecule (Fig. 2 right). Finally, \( \text{H}_2 \) stays on the surface until a temperature is reached that allows its evaporation, injecting the simplest molecule to the gas-phase of the ISM.

The role of the interstellar dust in the most complex chemistry that take place in the ISM is crucial. This is because they contribute to enrich the gas-phase with simple and quite complex molecular species formed onto them, and shield regions from the UV radiation, protecting in some cases large chemical chains. Indeed many molecules can form on grains. Some can form inside the mantles, and others on the grain surface, which can take part in further surface chemical reactions. The dust chemistry is in permanent association with the gas-phase chemistry (Hocuk & Cazaux, 2015). The molecular species formed in both the mantles and the dust surface can be injected into the gas-phase through evaporation due to the absorption of UV photons (photodesorption), or heating (thermal-desorption), or by escaping after total or partial grain disruption produced by collisions (see e.g. D'Hendecourt et al. 1985; Bisschop et al. 2007; Miura et al. 2017). Figure 3 illustrates some of these processes.

Figure 3: Schematic illustration of some processes that take place on icy grains. Image from Burke & Brown (2010).

Since the stars form in dark and cool regions plenty of interstellar dust which, as we see, favours the complex chemistry, understanding the chemical evolution of star-forming regions is a central topic. By one side, it is important because the chemistry is present along the whole process of stars and planets formation, which, moreover can lead to the biology; and on the other side, the chemistry can be used to probe the physical conditions of such regions (Gerner et al., 2014).

Next Section focuses on star formation processes in the context of the ISM as a dynamic and ever-changing environment.

3. Star formation

Taking into account that all in the ISM is in interaction, it is not possible to think the star formation as an isolated process. This is the reason why since some decades the so-called triggered star formation mechanisms are being investigated, mainly in the case of the formation of massive stars, in which one, or several events compress the molecular gas and initiate its collapse. In this Section, I review some and show the usual procedures to investigate them.

3.1. Collect and collapse

One of the star forming triggered processes that has been widely studied around \( \text{H} \) regions is the so called “collect and collapse” (CC). It was early proposed by Elmegreen & Lada (1977) and numerically treated by Whitworth et al. (1994a). In such process, during the supersonic expansion of an \( \text{H} \) region, a dense layer of material can be collected between the ionization and the shock fronts. Then this layer can be fragmented in massive condensations that then can collapse to lead the formation of new massive stars and/or clusters.

Figure 4: Example of a molecular shell surrounding an \( \text{H} \) region with presence of YSOs. The image was extracted from Pomarés et al. (2009). The borders of the \( \text{H} \) region are traced with the 8 \( \mu \)m emission (in gray) and the molecular shell, shown in contours, is mapped through the emission of \( ^{13}\text{CO} \). Red squares are the positions of Class I sources, i.e. the youngest YSOs.

To investigate whether the CC process is ongoing, firstly, using molecular and/or dust emission, it is looking for a dense molecular shell surrounding the ionized gas of an \( \text{H} \) region, or molecular massive fragments regularly spaced along the ionization front. Then, it is necessary to perform a search and analysis of point sources related to the molecular shell or fragments in order to determine if they are young stellar objects (YSOs). Finally, if a molecular shell and associated YSOs are found...
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surrounding the H\textsc{ii} (see Fig. 4), in order to establish whether the CC mechanism is responsible of that, a comparison between the dynamical age of the H\textsc{ii} region and the fragmentation time predicted by the theoretical models of Whitworth et al. must be done. This kind of investigations can be found in many works in the literature, see for example Deharveng et al. (2009), Pomarès et al. (2009), Zavagno et al. (2010), Duronea et al. (2017).

It is important to note that several processes can trigger star formation in the vicinity of H\textsc{ii} regions, and the mere finding of a molecular shell surrounding an H\textsc{ii} region not should be interpreted as a conclusive probe of the CC mechanism. In fact, this process can be acting in combination with others (e.g. Walch et al. 2015; Deharveng et al. 2015) such as the radiative driven implosion, which is discussed in the next Section.

3.2. Radiative driven implosion

Another triggered mechanism of star formation that may occur around H\textsc{ii} regions is the radiation-driven implosion (RDI), first proposed by Reipurth (1983). This process can begin when the ionization front from the H\textsc{ii} region moves over a molecular condensation, which generates a dense outer shell of ionized gas, usually called the ionized boundary layer (IBL). If the IBL is over-pressured with respect to the interior of the molecular condensation, shocks are driven into it compressing the molecular material until the internal pressure is balanced with the pressure of the IBL. At this stage, clumps within the compressed molecular feature can collapse leading to the creation of a new generation of stars (Bertoldi & McKee 1990; Lefloch & Lazareff 1994). Recent theoretical and observational studies of pillars, molecular features that are related to H\textsc{ii} regions, and possible star formation linked to them can be found in Tremblin et al. (2012, 2013) and Hartigan et al. (2015). Figure 5 shows pillar-like structures pointing to the open border of an H\textsc{ii} region, suggesting that they were sculpted by the ionization flux and hence are suitable features to investigate RDI. This kind of scenarios are compatible with the theoretical models developed by Gritschneder et al. (2009a,b), from which they show that the formation of pillar-like structures can be explained by the radiation from hot stars penetrating through low density interclump channels in the molecular clouds. In addition, these models also predict the formation of a new generation of stars in the pillars heads.

To investigate such a process it is necessary to estimate the ionized and neutral gas densities at the IBL and at the interior of the radiation exposed molecular structure, respectively. The first one can be obtained quite directly from, for example, observations of the radio continuum emission from the ionized gas at the IBL, or indirectly based on, knowing the spectral type of the H\textsc{ii} region exciting star(s), an estimate of the amount of UV photons arriving to the molecular structure. In the case of the neutral gas density at the interior of the irradiated molecular feature, it can be derived directly from molecular observations. Once one has the densities values, external and internal pressures can be derived in order to compare them and evaluate whether the RDI process is at work (e.g. Thompson et al. 2004; Ortega et al. 2013). On the other side, Bisbas et al. (2011) show, in numerical simulations, that it is also possible studying the RDI process only evaluating the incident ionizing flux over the molecular structure.

Additionally, this kind of molecular structures exposed to the UV ionization from an H\textsc{ii} region are perfect sites to probe the ion-molecule reactions. For instance, the detection of molecular species such as HCN, H\textsc{nc}, H\textsc{3}O\textsc{+}, HCO\textsc{+}, between others, towards the tips of the irradiated molecular structures allows us to study chemical chains in which the radiation has an important role and to probe the influence of the UV irradiation in the dense gas (Graninger et al. 2014; Chenel et al. 2016; Paron et al. 2017).

3.3. Cloud-cloud collisions

Taking into account the dynamics of the ISM, collisions between molecular clouds could happen frequently. Cloud-cloud collisions were proposed as an another important triggered star formation process. Early observational evidence of such a mechanism was presented by Loren (1976), and later it was numerically studied by Habe & Ohta (1992). The cloud-cloud collision generates a dense gas layer at the interface of the collision where it can be induced the formation of dense self-gravitating clumps (Fig. 6). At this interface the magnetic field and the gas turbulent velocity amplify, which increase the mass accretion rate of the clumps leading to the formation of high mass stars (Inoue & Fukui 2013).

To perform observational studies of this mechanism, signatures of collision must be detected using molecular lines observations, and young massive stellar objects related to the molecular structure have to be observed embedded in the junction of the colliding clouds. One important signature characteristic of the collision be-
between two dissimilar clouds is the cavity generated on the larger cloud (see Fig. 6). Thus, observing cavities and discarding that they are product of the expansion of an H\textsubscript{II} region and/or winds from massive stars is important to investigate whether collision between clouds could have happened (Torii et al., 2015). Another observational signature of cloud-cloud collision is the bridge feature that can be seen in a position-velocity diagram from emission of molecular lines (see Fig. 7). This feature probes the enhancement of the turbulent motion of the gas at the interface between both colliding clouds (Haworth et al., 2015; Fukui et al., 2016; Torii et al., 2017).

3.4. Intrinsic processes

After the above enumeration of some of the main triggered star formation mechanisms, this Section presents a few words concerning to some intrinsic processes related to the formation of a new star which have consequences in the surrounding ISM, such as jets and winds.

Figure 8 displays a typical sketch of the main star formation processes and features: an accretion disk that extracts matter from the molecular envelope and feeds the central object, while powerful winds emanate from the poles of it, forming bipolar jets that sweep up molecular material generating the so called molecular outflows. There is a lot of literature concerning to these star forming processes, for example a recent review about protostellar outflows can be found in Bally (2016), and for a more global treatment see McKee & Ostriker (2007), who presented a framework to build a comprehensive theory of star formation, that as the authors mentioned, will be tested by the next generation of telescopes. After a decade of this review, I think that we are beginning to do this work.

For instance, recently Bjerkeli et al. (2016) presented an important observational result: from molecular line observations towards a YSO in TMC1A using the Atacama Submillimeter Telescope Array, it was demonstrated that the outflowing gas is launched from an extended region, and not from a region very close to the protostar as shown in Fig. 8. This result tends to prove that the outflowing activity may be due to winds from the disk.

Another observational results that changed the ideal picture of Fig. 8, is that the jets and outflows do not always appears aligned. Jets may present S- and Z-shaped symmetries, which indicate that the outflow axis has changed over time, probably due to precession induced by a companion, interactions with companion stars, or by the misalignment between the protostar rotation axis and magnetic fields (Bally et al., 2007; Lewis et al., 2015). Additionally, C-shaped morphology in jets may indicate motion of surrounding gas or motion of the outflow source itself. Figure 9 displays, with great
detail, the typical features observed at near-IR of a precessing jet: a cone-shaped nebula with some arc-like features. These structures are evidences of a cavity cleared in the circumstellar material that shines at near-IR due to radiation from the central protostar that is scattered at the inner walls of the cavity, emission from warm dust, and lines emission ([FeII], shock-excited H2, between others). Studying the outflow (a)symmetries is an important issue because it provides information about the dynamical environment of the outflows engine and the interstellar medium in which they spread.

Finally, and related to the begining of this article, it is important to note that the stellar jets and outflows have deep implications in the chemistry of the cloud in which the stellar object is embedded. Either due to collisions between the jet and cloud, or the radiation generated by the central object and the jet itself, the chemistry can drastically change through ionization and/or evaporation of molecular species from the dust grains. Many molecules form at the interfaces between protostellar outflows and their natal molecular clouds (van Dishoeck & Blake, 1998; Lim et al., 2001; Williams et al., 2002; Codella et al., 2006; Rollins et al., 2014), and their observation sheds light on such star forming process and its interaction with the medium.

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Figure 9: Example of circumstellar features at near-IR observed towards a jet precessing YSO. The angular resolution of this image is about 0.5 arcsec, which taking into account the distance to the source, represents 400 AU. Image from Paron et al. (2016).
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