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The formation of prebiotic molecules in star-forming regions

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Abstract. New sensitive observations using the current generation of (sub)millimeter telescopes have revealed in several star-forming regions molecular species of different chemical families (e.g. sugars, esters, isocyanates, phosphorus-bearing species) that may play an important role in prebiotic chemistry, and eventually in the origin of life. The observed molecular abundances of complex organic molecules (glycolaldehyde, ethylene glycol and ethyl formate) are better explained by surface-phase chemistry on dust grains, although gas-phase reactions can also play an important role, as in the case of methyl isocyanate. The PO molecule - a basic chemical bond to build-up the backbone of the DNA - has been detected for the first time in star-forming regions. These new observations indicate that phosphorus, a key element for the development of life, is much more abundant in star-forming regions than previously thought.

Key words. Astrochemistry – Astrobiology – ISM: molecules – Stars: massive

1. Introduction

The origin of life is, along with the origin of the Universe, the most fascinating topic for the Human Being. We still need to understand how simple molecules combined together until forming large macromolecules essential for living organisms. Molecules with more than 5 atoms containing carbon, usually called complex organic molecules (COMs) by astrochemists, are considered the building blocks of life. Some chemical families, such as sugars, esters, isocyanates and phosphorus-bearing species, are of special importance to astrobiology because they play crucial roles in the formation of prebiotic macromolecules such as the deoxyribonucleic acid (DNA) or the adenosine triphosphate (ATP).

The unprecedented capabilities of the new generation of astronomical facilities have allowed us to detect in the interstellar medium many of these prebiotic species. This has opened a new window for astrobiology from an astrophysical/astrochemical point of view. Life is expected to emerge on planets, which form in protoplanetary disks surrounding the host star. Therefore, the study of the chemical composition of star-forming regions will give us important clues about how chemical complexity can grow in the insterstellar medium.

The formation of prebiotic molecules is under intense debate nowadays. On one side, some works suggest that they are formed on the surface on interstellar dust grains and then are subsequently desorbed to gas phase. On the other side, other recent works are based on efficient gas-phase formation routes. Only the comparison between multiple astronomical observations and the current models will give the answer to this topic.

I present here some results from recent observations of star-forming regions, where molecules with prebiotic interest (glycoladehyde, ethylene glycol, ethyl formate, methyl isocyanate, and phosphorus-bearing molecules) have been detected towards the astrochemical templates for high-mass (G31.41+0.31 and W51 e2) and low-mass (solar-type) star-forming regions (IRAS 16293-2422). I will briefly discuss how our findings can help us to understand the formation of these molecules in the interstellar medium, with the help of chemical models and laboratory experiments.

2. Complex organic molecules: glycolaldehyde, ethylene glycol, ethyl formate and methyl isocyanate

The simplest sugar-like molecule, glycolaldehyde (CH_2OHCHO), and its related alcohol ethylene glycol ($(CH_2OH)_2$) are key species for prebiotic chemistry. Glycolaldehyde can react with propenal to form ribose, a central constituent of ribonucleic acid, RNA. Despite their importance, little is known about their formation. Recent theoretical and experimental works have proposed different pathways for the formation of these species (e.g. Bennett & Kaiser 2007, Woods et al. 2012, 2013, Butscher et al. 2015, Fedoseev et al. 2015), but comparisons with observations are needed to disentangle between the different proposed scenarios.

Recently, SMA observations presented by Rivilla et al. (2017a) revealed the presence of ethylene glycol towards the massive star-forming region G31.41+0.31, where also glycoladehyde was previously detected (Beltrán et al., 2009). Comparing the molecular abundances in G31.41+0.31 and other high- and low-mass star-forming regions we find evidence of an increase of the $(CH_2OH)_2/CH_2OHCHO$ abundance ratio with the luminosity of the source. The most likely explanation for this behavior is that these two molecules are formed by different chemical formation routes not directly linked. We conclude that $(CH_2OH)_2$ is likely formed by the combination of two CH_2OH radicals on the surface of dust grains, while we favor the formation of CH_2OHCHO via the solid-phase dimerization of the formyl radical HCO.

Even a more complex organic molecule is ethyl formate, C_2H_5OCHO, which is the second simplest representative of the ester family after methyl formate (CH_3OCHO). Only two detections of ethyl formate had been reported, towards SgrB2N and Orion KL regions (Belloche et al. 2009, and Tercero et al. 2013, respectively), which strongly limits our understanding on how this molecule is formed in the interstellar medium. Then, we searched for this species towards another star-forming region, the chemically rich hot core W51 e2 using a spectral line survey carried out with the IRAM 30m telescope. In Rivilla et al. (2017b) we reported the detection of this species, with an abundance with respect to molecular hydrogen of $\sim 10^{-8}$. We compared for the first time the molecular abundances of ethyl formate observed in star-forming regions with the different chemical models based on grain-surface and gas-phase chemistry (Garrod et al. 2008 and Taquet et al. 2016, respectively), finding that the former may have a dominant role in the formation of ethyl formate.

Methyl isocyanate (CH_3NCO) is another COM with high prebiotic interest. This molecule, detected for the first time in space towards two massive star-forming regions (see Halfen et al. 2015 and Cernicharo et al. 2016), could play a role in the synthesis of chains of amino acids. Recently, two groups have also detected this species towards the solar-type system IRAS 16293-2422 (Martín-Domenech et al. 2017 and Ligterink et al. 2017) using ALMA observations. The latter group also carried out laboratory experiments irradiating interstellar ice analogs, finding that surface chemistry CH_3 and HNCO recombinations can be an efficient way to form CH_3NCO. Martín-Domenech et al. (2017) used the chemical model UCL−CHEM (Holdship et al. 2017) to evaluate the different formation routes proposed for CH_3NCO (surface and gas-phase chemistry), including the experimental results from Ligterink et al. The output of the chemical model indicates that both ice surface and gas-phase reactions are needed to explain the observed abundances of CH_3NCO.

3. Phosphorus in the interstellar medium: the missing prebiotic element

One of the key elements for the development of life is phosphorus. Chemical macromolecules containing phosphorus, such as phospholipids and phosphates, are essential for the structure and energy transfer in cells. Especially important is the chemical bond between phosphorus and oxygen, P-O, which is crucial for the formation of the backbone of the deoxyribonucleic acid, DNA, the macromolecule that contains the generic information of living organisms. The Chemistry Nobel Prize Sir Alexander Todd remarked the astrobiological importance of phosphorus when he said: *Where there is life, there is phosphorus*. For these reasons, the study of interstellar phosphorus is generating increasing interest in the last years. Very recently, the Rossetta mission discovered phosphorus in the comet 67P Churyumov-Gerasimenko among other prebiotic chemicals such us glycine, the simplest amino acid. However, our knowledge about phosphorus in the interstellar medium is still very poor. It is mandatory its study in star-forming regions, where stars, planets (and eventually life) are expected to arise.

With this in mind, we started several observational projects to study phosphorus-bearing species in star-forming regions. Fontani et al. (2016) presented 8 new detections of the PN molecule towards massive dense cores, which doubled the numbers of star-forming regions with the presence of phosphorus known so far. However, POwas not detected. Soon after, Rivilla et al. (2016) presented the first detections of PO towards two chemically rich star-forming regions: W51 e2 and W3(OH). PN was also detected simultaneously, and the molecular abundance ratio PO/PN is 1.8−3. To understand how phosphorus-bearing molecules are formed in star-forming regions we developed a chemical model based on Vasuynin & Herbst (2013) chemical network. The model shows that the phosphorus-bearing molecules freeze-out onto dust grains at the end of the collapse phase of the parental core and desorb once the protostars start to heat up the environment. The observed molecular abundances indicates that phosphorus is significantly more abundant in star-forming regions than previously thought by a factor of 25, which interestingly opens the possibility of discoveries of new phosphorus-bearing molecules.

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