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Organic molecules in protoplanetary disks

C. Favre[1,2]

[1] Univ. Grenoble Alpes, CNRS, IPAG, 414 Rue de la Piscine, 38400 Saint-Martin-d'Hères, France, e-mail: `cecile.favre@univ-grenoble-alpes.fr`

[2] INAF–Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, Firenze, 50125, Italy

Abstract. One of the major problem in Astrochemistry is whether the organic chemistry during the star and planet formation process is inherited by planets and small bodies of the final planetary system. Indeed, planets and comets formation occurs through the combination of dust and gas lying within the disks surrounding young stars. And, among the molecules found in comets, some of them have also been detected in the interstellar medium (ISM). This leads one to ask whether these molecules were altered or formed in the protosolar nebulae or whether they are of direct ISM heritage. Consequently, understanding the formation of organic molecules, especially those of prebiotic interest, and the mechanisms that lead to their incorporation in asteroids and comets, might very well be of crucial importance for understanding the emergence of life. Thanks to recent progress in radioastronomy instrumentation for (sub)millimeter arrays such as with ALMA and NOEMA (high angular resolution and high sensitivity), new results have been obtained. I will review some notable results on the detection of organic molecules, including prebiotic molecules, towards protoplanetary disks.

Key words. ISM: molecules – astrochemistry – protoplanetary disks – radio lines: ISM – submillimeter: planetary systems

1. Introduction

One of the most important questions of the chemistry of the Interstellar Medium (hereafter, ISM) is how, where and when (complex) organic molecules (i.e that contain more than 6 atoms, Herbst & van Dishoeck 2009) and potentially prebiotic molecules are formed? And in a context of an exogenous delivery of organic matter by the small bodies (i.e comets, asteroids) of the Solar System and their fragments (meteorites and micrometeorites), could this have a bearing on the origin of life on Earth? Important molecules for Life such as carboxylic acids (especially fatty acids that lead to the membrane formation), amino acids (among those, eight, including the glycine, are the first constituents of proteins) as well as nucleobases, and precursor of truly biotic molecules have all been detected in some of the small bodies (i.e comets, asteroids) of the Solar System and their fragments (meteorites and micrometeorites), that are remnants of our own protoplanetary disk, such as the Murchison meteorites (Pizzarello et al. 2006; Schmitt-Kopplin et al. 2010) and/or the comets C/2012 F6, C/2013 R1 and 67P/Churyumov-Gerasimenko (e.g. see Biver et al. 2014; Altwegg et al. 2016).

The formation of planets, along with that of the small bodies, occurs through the combi-

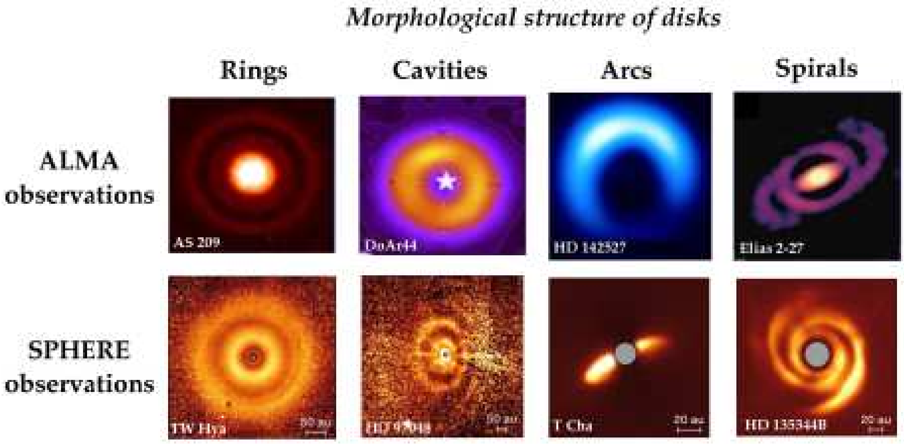

Fig. 1. Montage of the morphological diversity of disks as observed with ALMA (mm grains) and SPHERE (μm grains). The ALMA images are taken from Fedele et al. (2018), van der Marel et al. (2016), Casassus et al. (2012) and Pérez et al. (2016) for AS 209, DoAr44, HD 142527 and Elias 2-27, respectively. The SPHERE images (see Garufi et al. 2017) are taken from van Boekel et al. (2017), Ginski et al. (2016), Pohl et al. (2017) and Stolker et al. (2016) for TW Hya, HD 97048, T Cha and HD 135344B, respectively.

nation of dust and gas lying within the disks surrounding young stars. This leads one to ask whether the organic molecules found in the ISM were altered or formed in the protosolar nebulae or whether they are of direct ISM heritage. And in an interstellar–Earth connection, what are the key organic molecules? Although expected to be present in protoplanetary disks, the so called prebiotic molecules have not been detected in those objects yet. Nonetheless, the recent progress in radioastronomy instrumentation (high angular resolution, high sensitivity and large band correlator) for (sub-)millimeter arrays such as ALMA and NOEMA have opened a new window for the search for organic molecules in protoplanetary disks.

This paper is organized as follows: a description of the physical and chemical structure of a protoplanetary disk and how the physics strongly affect the chemistry is given in Section 2. Sections 3 and 4 list the up-to-date detections of organic molecules and their implications in Solar-type disks protoplanetary disks and Fu Ori objects. Conclusions are set out in Sec. 5.

2. Protoplanetary disks

Protoplanetary disks are composed of a mixture of dust and gas. The recent progress in instrumentation providing high resolution and sensitivity, such as for the Atacama Large Millimeter/ submillimeter Array (ALMA) and the Spectro-Polarimetric High-contrast Exoplanet (SPHERE) facility, has allowed astronomers to image the morphology of several protoplanetary disks (see e.g. Fedele et al. 2018; Garufi et al. 2017; Pohl et al. 2017; van Boekel et al. 2017; Ginski et al. 2016; van der Marel et al. 2016; Stolker et al. 2016; Pérez et al. 2016; Casassus et al. 2012). Interestingly enough, these observations have revealed a morphological diversity of disks as shown in Figure 1. Indeed, most of the disks display the following structure: gaps and rings (that may be the result of a forming planet, see e.g Baruteau et al. 2016; Bae et al. 2017, 2018;

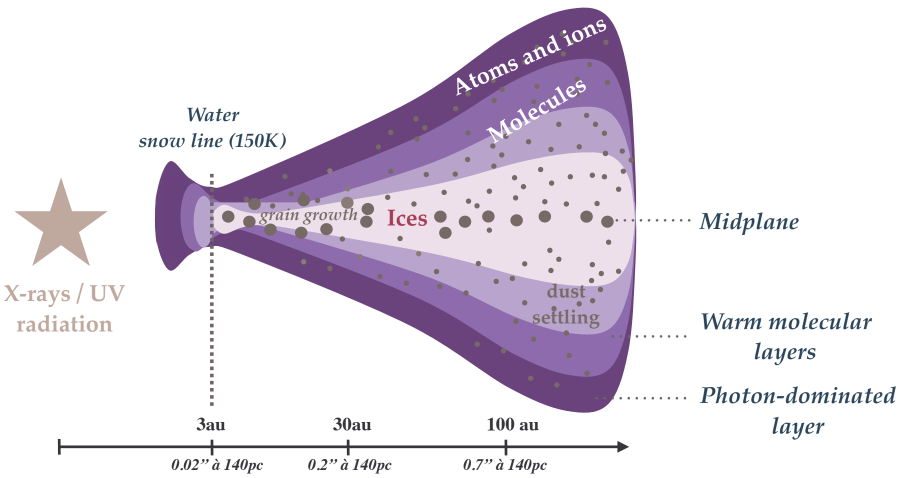

Fig. 2. Sketch of physical and chemical structure of protoplanetary disks.

Müller et al. 2018; Favre et al. 2019), cavities or spirals.

2.1. Physico-chemistry of protoplanetary disks

From a chemical point of view, protoplanetary disks are also complex: ions are located at the disk surface, ices (and frozen material on their surfaces) are in the disk mid-plane while the gas molecular content lies within different molecular layers between the disk surface and the mid-plane as illustrated Figure 2. However, this apparent stratification of the molecular content is affected by the physical conditions of the environment. Indeed, owing to strong density, temperature and radiation gradients (stellar UV / Xrays), dust settling and drifting that are taking place in protoplanetary disks (see Fig 2), the different layers of the disks are coupled through vertical and radial mixing processes. A more detailed description of the physico-chemistry that is occurring in disk can be found in Henning & Semenov (2013) and Dutrey et al. (2014).

The resulting interaction between the gas and the dust in disks is therefore dynamically, thermally and chemically dependent. The best example of the dust and gas interaction is the observed deficit in gaseous carbon and oxygen in proto-planetary disks (Favre et al. 2013; Schwarz et al. 2016; Kama et al. 2016; Bergin et al. 2016; Semenov et al. 2018). More specifically, the carbon might be locked in CO_2 and/or in carbon chains (C_xH_y) that are frozen-out onto the icy surface of grains (see Aikawa et al. 1997; Reboussin et al. 2015) while the oxygen, mainly present in H_2O, is removed from the gas phase and condensed onto large dust grains which sediment to the disk mid-plane (see Bergin et al. 2016; Semenov et al. 2018). A salient point is that this gaseous C and O deficit is only observed in low mass proto-planetary disk. This leads one to wonder if it

Table 1. Molecular inventory of protoplanetary disks surrounding T-Tauri and/or Herbig stars.

Atoms	
C_I, C_{II}, O_I	Sturm et al. (2010),Meeus et al. (2012),Du et al. (2015), Kama et al. (2016)
Ions	
HCO^+, $H^{13}CO^+$, DCO^+, N_2H^+, CH^+	Dutrey et al. (1997, 2007), van Dishoeck et al. (2003), Thi et al. (2011)
N_2D^+	Qi et al. (2008, 2013a), Öberg et al. (2015a), Huang & Öberg (2015)
Carbon reservoirs?	
CO, CO_2	Koerner & Sargent (1995), Pontoppidan et al. (2010)
Simple species	
^{13}CO, $C^{18}O$, OH, HD	Dutrey et al. (1996), Pontoppidan et al. (2010),
	Bergin et al. (2013), Favre et al. (2013), McClure et al. (2016)
S-bearing molecules	
CS, SO, H_2S	Dutrey et al. (1997), Guilloteau et al. (2013), Phuong et al. (2018)
^{13}CS, $C^{34}S$, H_2CS	Le Gal et al. (2019)
N-bearing molecules	
CN, HCN, $HC^{15}N$, $H^{13}CN$,	Dutrey et al. (1997), Qi et al. (2008), Salinas et al. (2016)
HNC, DCN, NH_3	Guzmán et al. (2017), Booth et al. (2019)
Carbon chains	
CCH, C_2H_2, c-C_3H_2, HC_3N	Dutrey et al. (1997), Pontoppidan et al. (2010),
	Henning et al. (2010), Chapillon et al. (2012), Qi et al. (2013b),
	Öberg et al. (2015b),Bergner et al. (2018)
Water	
H_2O	Bergin et al. (2010), Hogerheijde et al. (2011),
	Fedele et al. (2012), Podio et al. (2013)
O-bearing molecules	
H_2CO	Qi et al. (2013a),Loomis et al. (2015), Öberg et al. (2017)
	Carney et al. (2017), Guzmán et al. (2018),Podio et al. (2019)
t-HCOOH	Favre et al. (2018)
Complex organic molecules	
CH_3OH	Walsh et al. (2016)
CH_3CN	Öberg et al. (2015b),Bergner et al. (2018),Loomis et al. (2018)

only happens to low mass disks and what is the influence on planetary formation?

2.2. Interferometry for astrochemical studies: sensitivity & resolution

The chemistry (in gas phase and/or on the icy surface of grain mantles) that is taking place in protoplanetary disks reflects the diversity and inhomogeneity of these objects that are the final stage of planetary formation but still need to be understood. To access the molecular content in disk, interferometers such as ALMA or NOEMA (Northern Extended Millimiter Array) are needed.

The most chemically active regions are actually expected to be small and lie close to the central object, i.e. within the inner 50–100 AU[1]. This makes the detection of large (organic) molecules, difficult (see Walsh et al. 2014) and requires the use of high angular. Indeed, at the distance of the Taurus cloud (i.e. about 140 pc): 0.7″ is needed to image the inner 100 AU of a disk, 0.4″ for the inner 50 AU and 0.07″ for the inner 10 AU. It is also important to note that high sensitivity (i.e high signal-to-noise ratio) is key to detect organic molecules which harbours faint / weak spectral lines (see e.g. Favre et al. 2018). Incidentally,

[1] 1 AU: distance between the Sun and the Earth.

other approaches such as the line stacking (see e.g. Walsh et al. 2016) or the matched filtering (Loomis et al. 2018) are likely useful for detecting weak transitions.

3. Organic molecules in solar-type protoplanetary disks

Of the over 30 molecules, including some isotopologues, have been detected in different circumstellar disks surrounding T Tauri and/or Herbig stars. Table 1 lists these different molecules.

Among the complex species, there are hydrocarbons, such as c-C_3H_2 (Qi et al. 2013b; Bergin et al. 2016), cyanides, HC_3N and CH_3CN (Chapillon et al. 2012; Öberg et al. 2015b) and the two following organic O-bearing molecules, methanol, CH_3OH (Walsh et al. 2016), and formaldehyde, H_2CO (Qi et al. 2013a; Öberg et al. 2017; Guzmán et al. 2018; Podio et al. 2019). The latter are important for complex organic chemistry as they are believed to be the first step (i.e. parent species) toward larger and more complex molecules in the gas phase and/or at the icy surface of grain mantles (see, e.g. Charnley & Rodgers 2005). These results imply that chemistry leading to complex organic molecules likely takes place in those objects.

In addition, Favre et al. (2018) have recently reported the first detection of formic acid, HCOOH, towards the disk surrounding a Sun-like young star. This discovery is important in a context of early Earth-Interstellar connection as HCOOH stands as the basis for synthesis of more complex carboxylic acids (R-COOH) used by life on Earth. Actually, this species is involved in a chemical route leading to glycine, the simplest amino acid (Basiuk 2001; Redondo et al. 2015).

These finding strongly suggest that a rich organic chemistry likely takes place at the verge of planet formation in protoplanetary disks.

4. Organic in Fu Ori object: the case of V883 Ori

The V883 Ori star is a FU Orionis object located at 400 pc (Kounkel et al. 2017) with an accreting rate of 7.5×10^{-5} M_{sol} yr^{-1} (see, Ruíz-Rodríguez et al. 2017). This fast accretion rate, typical of FU Orionis object, is about 2-3 orders of magnitude larger than the one of T-Tauri objects and therefore leads to episodic outbursts during the star evolution (see Hartmann & Kenyon 1996). In that light, the protoplanetary disk surrounding V883 Ori is warmer than that of typical T–Tauri / Herbig stars. As a result, water (H_2O) has an evaporation radius of about 42 au towards V883 Ori while the water snow–line is usually at $\leq$10au for T-Tauri objects. This leads ices to sublimate out to larger radii (i.e. large emitting zone) and therefore make possible the observation of the grain molecular content in the gas phase via thermal desorption.

In that context, using ALMA observations van 't Hoff et al. (2018) and Lee et al. (2019) have reported the detection of five complex organic molecules, including methanol and its ^{13}C isotopologues, in the disk surrounding V883 Ori (see Table 2). Interestingly enough, the derived physical conditions (temperature of 100 – 120 K, molecular column densities as high as 10^{16}–10^{17} cm^{-2}, see Lee et al. 2019) are similar to the ones observed in typical hot corinos (Caselli & Ceccarelli 2012; Ceccarelli et al. 2017).

These findings lead one to think that one should be able to observe in V883 Ori the molecular content that will be frozen at a later stage and that will likely be incorporated and/or delivered to the forming planets and comets.

5. Conclusions

In summary, protoplanetary disks are morphologically and physico-chemically complex systems and the search for large organic molecules in thess environments still remain difficult. Nonetheless, complex organic molecules (N- and O-bearing species), including bricks of prebiotic molecules, have been observed in

Table 2. Molecular inventory of the protoplanetary disk surrounding surrounding the Fu Ori object V883 Ori.

Large N-bearing molecules	
CH_3CN	Lee et al. (2019)
Complex O-bearing molecules	
CH_3OH	van 't Hoff et al. (2018), Lee et al. (2019)
$^{13}CH_3OH$, CH_3CHO	Lee et al. (2019)
CH_3COCH_3, $HCOOCH_3$	Lee et al. (2019)

protoplanetary disks. These interferometric observations strongly imply that chemistry leading to molecular complexity likely takes place at the verge of planet formation in protoplanetary disks. Finally, it is important to note that even with the capabilities of ALMA (resolution and sensitivity) observations of large organic species in such environment remain challenging.

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