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WATER AND COMPLEX ORGANIC MOLECULES IN THE WARM INNER REGIONS OF SOLAR-TYPE PROTOSTARS

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Abstract. Water and complex organic molecules play an important role in the emergence of Life. They have been detected in different types of astrophysical environments (protostars, prestellar cores, outflows, protoplanetary disks, comets, etc). In particular, they show high abundances towards the warm inner regions of protostars, where the icy grain mantles thermally desorb. Can a part of the molecular content observed in these regions be preserved during the star formation process and incorporated into asteroids and comets, that can deliver it to planetary embryos through impacts? By comparison with cometary studies, interferometric observations of solar-type protostars can help to address this important question. We present recent results obtained with the Plateau de Bure interferometer about water deuteration, glycolaldehyde and ethylene glycol towards the low-mass protostar NGC 1333 IRAS2A.

Keywords: astrochemistry, astrobiology, ISM: individual objects: NGC 1333 IRAS2A, stars: formation , stars: protostars, ISM: molecules

1 Introduction

Star-forming regions are known to show a very rich chemistry. Numerous molecules are especially detected towards Class 0 protostars, both in the warm inner regions and in the cold outer envelope. The presence of these molecules can be explained both by gas phase and grain surface chemistry. A lot of complex organic molecules (COMs) are found in the inner regions (e.g., Bottinelli et al. 2004, 2007; Bisschop et al. 2008) and are thought to be released in the gas phase with water once the temperature is sufficiently high ($T > 100\,\mathrm{K}$) to desorb the icy grain mantles. These regions are called hot corinos (Ceccarelli 2004).

Asteroids and comets are also chemically rich. Water was detected in different comets (e.g., Mumma et al. 1986) and asteroids (Campins et al. 2010; Küppers et al. 2014). COMs such as ethylene glycol and formamide are also known to be present in comets (Biver et al. 2014). Glycine, an amino-acid, was even found by Elsila et al. (2009) in the cometary samples of the STARDUST mission. A lot of COMs, amino acids and sugars were also found in meteorites (e.g., Schmitt-Kopplin et al. 2010). It was consequently suggested that water and prebiotic molecules (i.e. amino-acids and sugars) could have been delivered to Earth by impacts of asteroids and/or comets, which would have probably played an important role in the emergence of Life.

The question then arises: can the molecular content observed during the Class 0 stage be preserved during the star formation process (at least partially) until the formation of planets, comets and asteroids or is it completely reprocessed? To answer this question, it is therefore important to study the chemistry in the warm inner regions of protostars, where planets are supposed to form at a later stage. The aims are first to compare it with comets and asteroids and determine any similarity or variation between molecules, and secondly to better understand how this Class 0 molecular content formed.

We present recent results obtained with the Plateau de Bure Interferometer (PdBI) towards low-mass protostars. Section 2 is focused on water deuterium fractionation, while Section 3 is dedicated to glycolaldehyde and ethylene glycol. Perspectives are presented in Conclusion.

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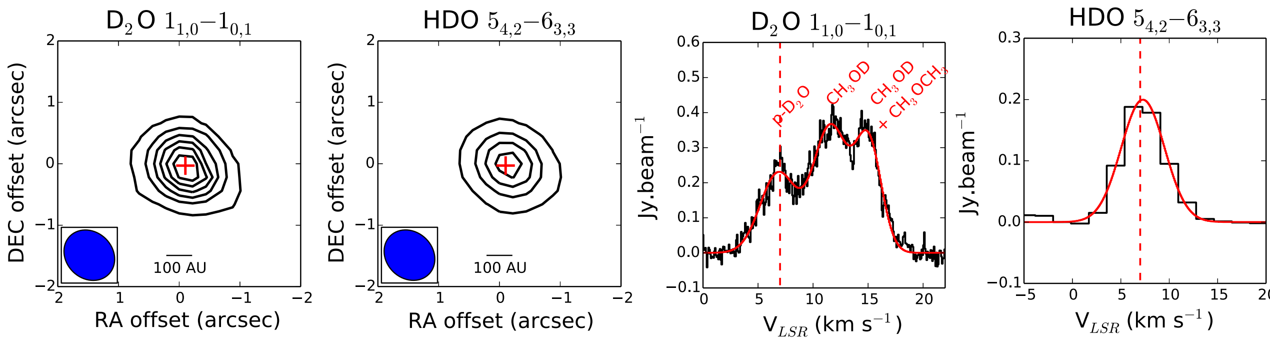

Fig. 1. Observations of the D_2O $1_{1,0}$-$1_{0,1}$ and HDO $5_{4,2}$-$6_{3,3}$ transitions towards the protostar NGC 1333 IRAS2A with the PdBI. Left panels: integrated intensity maps. Right panels: continuum subtracted spectra. Figure from Coutens et al. (2014).

2 Water deuteration

The determination of deuterium fractionation ratios is very helpful to understand how molecules form and to follow their evolution. Indeed, the deuterium fractionation can be enhanced by a few reactions, such as the reaction $H_3{}^+$ + HD $\rightarrow$ H_2D^+ + H_2 that is only efficient at low temperatures and high densities. If molecules formed in a cold and dense environment, their deuterium fractionation ratios should therefore be higher by several orders of magnitude than if they formed in the gas phase at high temperature.

Water can form through different mechanisms: i) ion-molecule gas phase reactions, ii) high-temperature gas phase reactions (typical of shocks or hot cores) and iii) hydrogenation of atomic and molecular oxygen on grain surfaces (in cold and dense regions) (see van Dishoeck et al. (2013) for more details). With the determination of the water deuterium fractionation ratios and chemical modeling, it is then possible to constrain the origin of water.

2.1 HDO/H_2O ratios towards solar-type protostars and comets

The HDO/H_2O ratio* was determined in the inner regions of several Class 0 protostars by Persson et al. (2014) using PdBI data. The values range between 6×10^{-4} and 2×10^{-3} (see Figure 6 in Persson et al. 2014). Comets also show various values. The ratios found in Oort cloud comets are on average slightly lower than in the warm inner regions of protostars (Bockelée-Morvan 2011), but could be consistent with some of the protostars. The HDO/H_2O ratio is lower for two Jupiter family comets that were studied with the HIFI spectrometer onboard Herschel and consistent with the terrestrial value ($\sim 3 \times 10^{-4}$, Hartogh et al. 2011; Lis et al. 2013), but the in-situ measurement obtained towards another Jupiter family comet in the framework of the Rosetta mission is higher and in agreement with the protostellar values (Altwegg et al. 2015). The similarity of the HDO/H_2O ratios suggest that at least a part of the cometary water content could originate from the first phases of star formation. It is also supported by a theoretical study that showed that a total reprocessing of the chemistry in the protoplanetary disk would lead to HDO/H_2O ratios that are too low compared to the values found in comets and Earth's oceans (Cleeves et al. 2014).

2.2 Determination of the D_2O/HDO ratio towards NGC 1333 IRAS2A

Although D_2O has not been detected towards comets so far, interferometric studies of this isotopologue towards low-mass protostars can help to understand the origin of water in the warm inner regions of these objects. Observations of the D_2O $1_{1,0}$–$1_{0,1}$ transition were carried out towards the source NGC 1333 IRAS2A with the PdBI, leading to the first interferometric detection of D_2O towards a low-mass protostar (Coutens et al. 2014, see Fig. 1). The D_2O/HDO ratio was found to be surprisingly high ($\sim 1.2 \times 10^{-2}$) compared to the HDO/H_2O ratio ($\sim 1.7 \times 10^{-3}$). None of the grain surface chemical models (including the doubly deuterated form of water) published so far show a D_2O/HDO ratio higher than the HDO/H_2O ratio. This consequently suggests that

*The HDO/H_2O ratio is equal to twice the water D/H ratio.

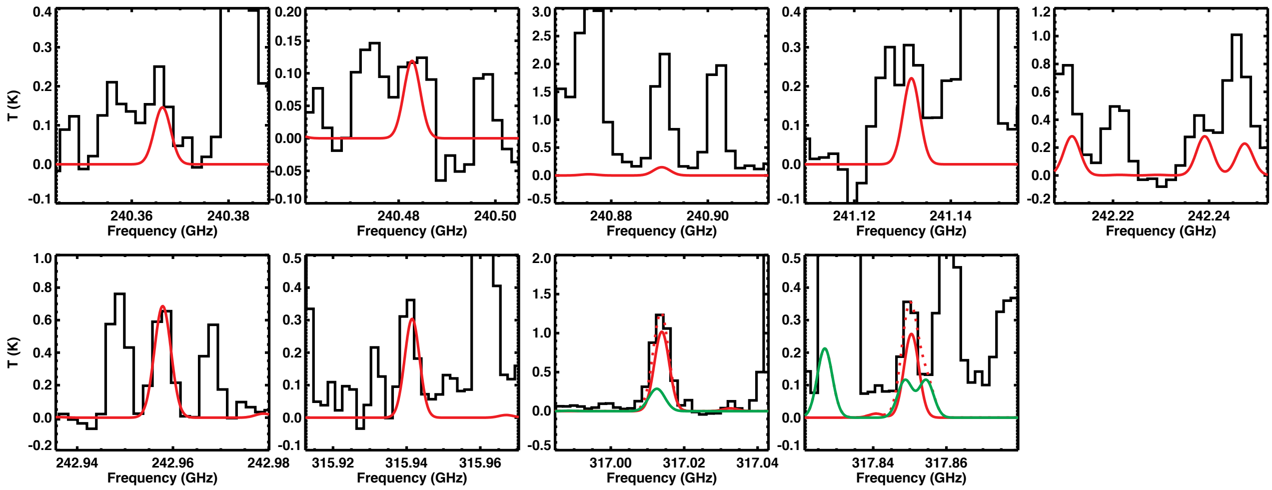

Fig. 2. Observed lines of glycolaldehyde toward the protostar NGC 1333 IRAS2A (in black). The LTE modeling of glycolaldehyde is shown in red. The contribution of methyl formate is shown in green. Figure from Coutens et al. (2015).

either an ingredient is missing in the understanding of deuterium fractionationation processes, or that high temperature gas phase reactions also take place in the warm inner regions of protostars. Indeed, in the second case, the thermal desorption of the icy grain mantles would explain the high D_2O/HDO ratios, while the high temperature gas phase reactions would produce a lot of H_2O (but only a little of deuterated water), which would lead to a decrease of the HDO/H_2O ratio.

3 Glycolaldehyde and ethylene glycol

Glycolaldehyde (CH_2OHCHO) is the simplest form of sugar and is thought to play a role in the formation of biological molecules. It was also shown that this molecule could survive during impact delivery to planetary bodies (McCaffrey et al. 2014). The reduced alcohol of this species is named ethylene glycol $(CH_2OH)_2$. While ethylene glycol was detected towards three comets, glycolaldehyde was not[†], leading to an ethylene glycol-to-glycolaldehyde (hereafter EG/GA) ratio higher than 3–6 (Crovisier et al. 2004; Biver et al. 2014). Glycolaldehyde was detected for the first time towards a low-mass protostar (IRAS 16293-2422) with the Atacama Large Millimeter/submillimeter Array (ALMA) by Jørgensen et al. (2012). Local thermal equilibrium analyses of glycolaldehyde and ethylene glycol give a lower EG/GA ratio of about 1 (Jørgensen et al. in prep.), which would suggest that a reprocessing of the chemistry takes place between the Class 0 stage and the formation of comets.

We analyzed some observations of another low-mass protostar, NGC 1333 IRAS2A, to determine if the EG/GA ratio was similar to IRAS 16293-2422. Eight lines of glycolaldehyde and more than thirty lines of ethylene glycol were successfully detected towards this source (Coutens et al. 2015, see Fig. 2). The EG/GA ratio was estimated at about 5, which means that it is consistent with the lower limits found in comets and higher than the value in IRAS 16293-2422. Several hypotheses can be proposed to explain the different ratios measured in NGC 1333 IRAS2A and IRAS 16293-2422. If the EG/GA ratio was initially the same on grains, it would indicate that some gas phase reactions are able to destroy (or possibly form) one of the two molecules more efficiently (after their desorption in the hot corino). A different sublimation temperature for the two molecules could also be possible. More experimental and theoretical work would be needed to know if these scenarios are possible. Experimental studies show, however, that the EG/GA ratio can vary on the grains (Öberg et al. 2009). It is especially sensitive to the CH_3OH:CO composition of the UV irradiated ices. A composition of pure CH_3OH leads to high EG/GA ratios (> 10), while a CH_3OH:CO 1:10 ice mixture produces low EG/GA ratios (< 0.25). It could consequently mean that ices in NGC 1333 IRAS2A were richer in methanol than in IRAS 16293-2422. This scenario seems plausible, as the gas-phase abundance of CH_3OH is higher towards

[†]A first detection of glycolaldehyde was recently presented in Goesmann et al. (2015).

NGC 1333 IRAS2A, while the CO abundances are similar (Schöier et al. 2002; Jørgensen et al. 2002, 2005). It is possible that CH_3OH formed more efficiently (by hydrogenation of CO) in NGC1333 IRAS2A, because this source shows lower H_2 densities than IRAS 16293-2422 (see Fig. 5 in Coutens et al. 2015). If ethylene glycol forms through hydrogenation of glycolaldehyde, it would explain why the EG/GA ratio is higher when the CH_3OH/CO ratio is higher.

4 Conclusion

Studying the chemistry in Class 0 protostars is important to understand how the molecules form and how they evolve between this stage and the formation of comets, asteroids and planets. Recent studies on deuterated water and COMs show that similarities can be observed between low-mass protostars and comets. The results on glycolaldehyde and ethylene glycol in NGC 1333 IRAS2A and IRAS 16293-2422 illustrate the need for investigating a higher number of sources, first to know if the chemistry in low-mass protostars is relatively similar and secondly to understand possible variations. Precise D_2O/HDO ratios will be soon obtained for the protostar IRAS 16293-2422 in the framework of an ALMA project (Coutens et al. in prep). With ALMA and the NOrthern Extended Millimeter Array (NOEMA), it will also be possible to investigate intermediary stages (Class I and Class II protostars) to better understand the evolution of the chemistry from the Class 0 stage to the formation of planets.

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