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ASTROCHEMISTRY DURING THE CLASS I PHASE: THE PROTOSTELLAR HERITAGE

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Abstract. Solar System is the result of a complex star formation process still far to be fully understood. Chemical complexity builds up at each step of this process, starting from simple molecules and ending up with prebiotic species, until the appearance of life on Earth. It is still unclear how the chemical complexity evolves during the process leading to the formation of a Sun and its planetary system and if the chemical complexity we observe nowadays is inherited from the early protostellar stages or, instead, if there is a complete chemical reset during the star formation process. A powerful way to start answering these questions is by comparing the observed astrochemical content in young protostars with that in comets and asteroids, i.e. with the most pristine known material from which our Solar System formed. Protoplanetary disks observations suggest that planets could start to form very early when the protostar is still embedded in a prominent envelope (less than 1 Myr). For this reason, young protostellar disks in the Class 0/I stage are the perfect laboratory where to study the initial conditions and the chemical content of planetesimal formation. I will show how we can explore the chemical composition of young protostellar systems through multiwavelenght observations using both single-dish telescopes and interferometer to sample the different spatial scales, from the infalling envelope ($\sim$ 10000 au) down to the planet formation region ($\sim$ 50 au).

Keywords: astrochemistry, star formation, large carbon chains

1 Introduction

How does chemical complexity change during the process leading to the formation of a Sun and its planetary system? Is the chemical richness of a solar-like planetary system partially inherited from the early stages or is there a complete chemical reset? Recent evidence suggests that the formation of planets probably begins already in young protostellar discs (Class I phase $\geq 10^5$ yr). Therefore, the study of their chemical compositions represents a key step in our understanding of the initial material available for the formation of the planets. The protostellar phase is characterized by the molecular complexity blooming: when the inner 100 au protostellar envelope are heated at temperatures larger than 100 K, dust mantles products thermally sublimate and enrich the chemical composition of the gas (the so-called hot-corino phase). In addition, dramatic changes in the molecular abundances are expected also because of a warm gas-chemistry at work. While hot-corinos in Class 0 sources are relatively well-known, very little has been done so far to study the overall composition of more evolved Class I sources (age $\sim 10^5$ yr), which represent the link between the protostellar stage and the planetary system formation.

I will focus on the chemical complexity observed in Class I protostars. In particular, I will show the results we have obtained from the ASAI (Lefloch et al. 2018) and SOLIS (Ceccarelli et al. 2017) IRAM Large Programs and, more recently from FAUST (Bianchi et al. 2020), the first ALMA Large Program focused on astrochemistry. Using deuterated molecules and complex organic molecules, I will compare the chemical richness observed in Class I protostars with those observed in younger Class 0 protostars and in comets, representing the most pristine material in our solar system. I will present the possible evolutionary trends in order to study the inheritance scenario. I will also report future perspectives on Class I protostar studies and molecular exploration for the advent of SKA.

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2 The IRAM Large Programs ASAI and SOLIS

SVS13-A is the first Class I protostar for which a complete census of iCOMs emission has been obtained thanks to the synergy of two IRAM Large Programs: ASAI (Astrochemical Survey At IRAM-30m; Lefloch et al. 2018) with the 30m antenna and SOLIS (Seeds Of Life In Space; Ceccarelli et al. 2017) with the NOEMA interferometer. Thanks to the ASAI high-sensitivity unbiased spectral survey of the 3, 2 and 1.3 mm bands, we detected and analysed several emission lines from deuterated species and iCOMs. The complementary high-sensitivity and high-spatial resolution interferometric maps from SOLIS provided information on the molecular gas spatial distribution, allowing a precise determination of gas physical conditions (see Fig. 1). Different tracers such as deuterated formaldehyde, thioformaldehyde, cyanoacetylene, methanol, methyl cyanide and, water were used to reconstruct the physical and chemical structure of the protostellar system (Codella et al. 2016; Bianchi et al. 2017, 2019a). In general, the measured deuteration show a chemical connection among the different evolutionary stages. Interestingly, methanol deuteration seems to decrease in SVS13 A with respect to younger Class 0 sources, possibly indicating chemical evolution. Beside deuterated species, emission from several iCOMs such as ketene, acetaldehyde, methyl formate, dimethyl ether and ethanol, revealed for the first time a rich hot corino chemistry towards the source (Codella et al. 2016; Bianchi et al. 2019b). The comparison between iCOMs abundance ratios in SVS13 A with those measured in younger Class 0 protostars brought to light several similarities, suggesting that chemical complexity is transferred from the Class 0 to the Class I stage.

3 The ALMA FAUST project

The prototypical Class I source L1551 IRS5 has been observed as part of the ALMA Large Program FAUST (Fifty AU Study of the chemistry in the disk/envelope system of Solar-like protostars; Bianchi et al. 2020). More specifically, FAUST is the first ALMA Large Program dedicated to astrochemical studies and it is designed to survey the chemical composition of a sample of 13 Class 0 and I protostars at the planet formation scale (from $\sim$ 1000 down to $\sim$ 50 au. We detected in L1551 IRS 5 several emission lines from iCOMs (see Fig. 2) such as methanol (CH_3OH) and its most abundant isopotologue (CH_2DOH), as well as methyl formate ($HCOOCH_3$) and ethanol (a-CH_3CH_2OH). Line emission is bright toward the north component (N), although a hot corino in the south component, cannot be excluded. The non-LTE analysis of the methanol lines towards N provides constraints on the gas temperature ($\sim$ 100 K), density ($n_{H_2} \geq 1.5 \times 10^8$ cm^{-3}) and emitting size ($\sim 0\farcs15$, i.e. $\sim$ 10 au in radius). The lines are predicted to be optically thick, the $^{13}CH_3OH$ line having an opacity $>$ 2. The methyl formate and ethanol column densities relative to methanol are $\leq$ 0.03 and $\leq$ 0.015, respectively, compatible with those measured in Class 0 sources. Thus, FAUST observations towards L1551 IRS5 agree with little chemical evolution in hot corinos from Class 0 to I, as previously suggested by the ASAI and SOLIS results.

4 Evidences for chemical inheritance ?

A way to test the inheritance scenario is to compare the relative abundances measured in young Class 0/I protostars with those measured in Solar System comets. Such an example is given in Fig. 3, where the protostellar molecular abundance ratios are compared with those observed in the comet 67P/Churyumov-Gerasimenko (ROSETTA mission, e.g. Rubin et al. 2019). Molecular abundance ratios are normalized to methanol and isomers are added because the ROSETTA mass spectrometer is not able to distinguish among them. More specifically, Fig. 3 shows measurements of SVS13-A, L1551 IRS5 and Ser-emb17 (Class I hot corinos), as well as younger Class 0 sources (Ser-emb1, Ser-emb8, HH212, IRAS16293-2422, IRAS4A, IRAS2A). Once considered the uncertainties, some iCOMs show a good agreement (within a factor of 10) suggesting chemical inheritance from the early stages (see also Drozdovskaya et al. 2019). Future perspectives include, as a first step, observational efforts to chemically characterise a larger sample of protostellar sources. In this respect, the forthcoming results of dedicated Large Programs, such as FAUST (Bianchi et al. 2020), will represent a major step ahead. On the other hand, complementary observations at radio wavelengths, for example using JVLA and, in a near future, SKA will be fundamental to overcome several limitations related to (sub-) mm-observations, such as dust opacity. An enlightening example is represented by the protostellar disk in HH212 as observed by ALMA down to 10 au scales (Lee et al. 2019): the continuum emission shows a dark equatorial lane due to high dust opacity, plus a rich iCOMs gas, detected only on the surface disk layers. Either (i) molecular abundance dramatically decreases in the equatorial disk, or (ii) iCOMs detection is hampered by the high opacity continuum (see e.g. De Simone et al. 2020). A decrease of the flux of molecular lines towards the central regions has been also observed using ALMA in more evolved Class I disks (see e.g. ALMA-DOT, Garufi et al. 2021). Only interferometric observation in the cm-domain can unveil the gaseous composition of protostellar disks mid-plane, the most interesting region for planets formation.

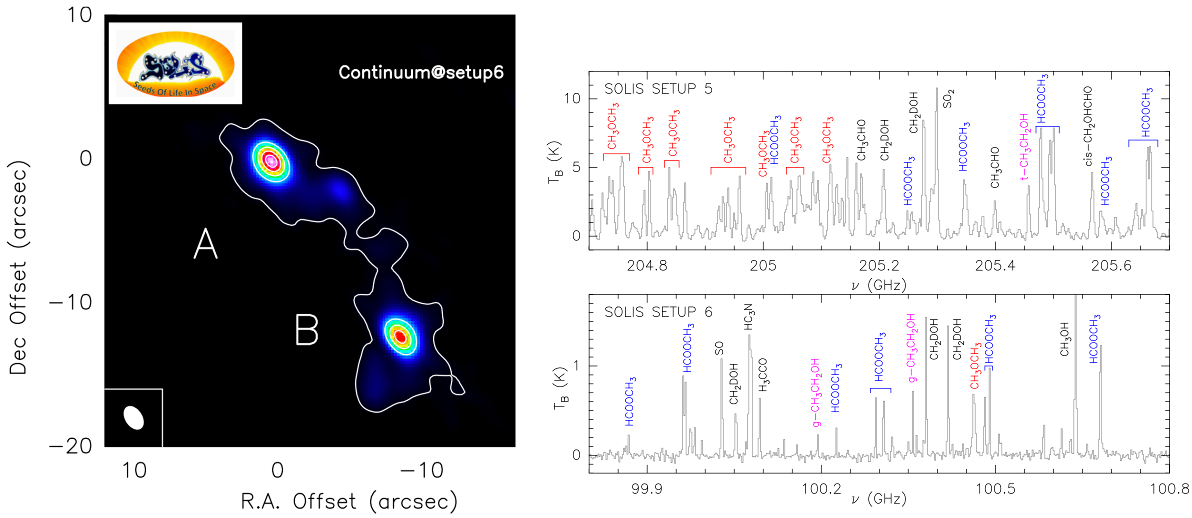

Fig. 1. Left: Continuum emission of the SVS13 system as observed by SOLIS NOEMA at 82 GHz. **Right:** Selected windows from SOLIS NOEMA observations, extracted towards the Class I protostar SVS13-A. Spectra show bright emission lines from several iCOMs including ethanol, methyl formate, acetaldehyde, dimethyl ether.

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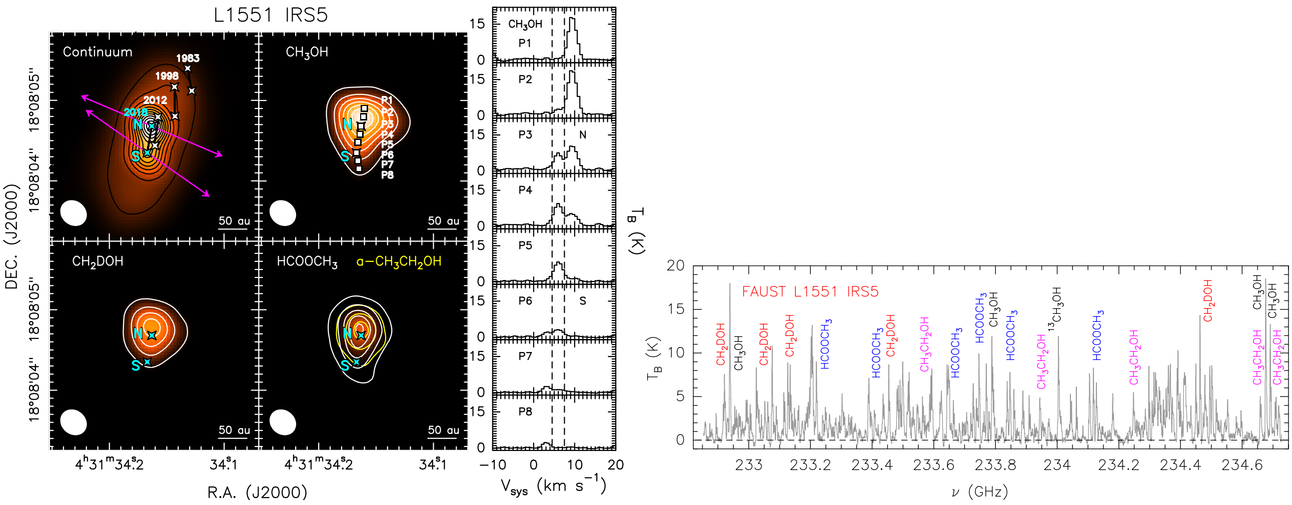

Fig. 2. Right panel: Dust and line emission as observed by FAUST towards the Class I protostellar system L1551 IRS5 (Bianchi et al. 2020). The white stars in the upper left panel indicate the positions of the binary system components (indicated as N, northern, and S, southern) measured from 1983 to 2018. The magenta arrows indicate the jet directions (Rodríguez et al. 2003). Emission from methanol and its deuterated isotopologue, methyl formate, and ethanol is detected on spatial scales comparable to our Solar System ($\sim$ 50 au). The ALMA beam is reported as a white ellipse in each panel. Maps show that iCOMs emission is present both in N and S, but it is brighter towards N, suggesting the presence of at least one hot corino. The white squares, labelled from P1 to P8, are the different positions where the spectra displayed on the right panels are extracted. The vertical dashed lines mark the systemic velocity inferred towards N (+7.5 km s1) and S (+4.5 km s1), respectively. **Right panel**: Observed line spectra (in T_B scale) towards the continuum peak position of the northern protostar N. The spectra show the chemical richness associated to the hot corino.

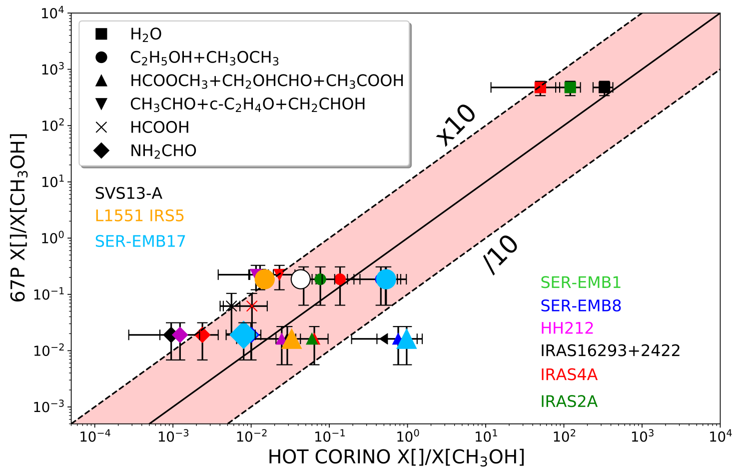

Fig. 3. Comparison of molecular abundance ratio of iCOMs observed in Class 0 and Class I hot corinos, including SVS13-A and L1551 IRS5, with those observed in the comet 67P/Churyumov-Gerasimenko (ROSETTA mission). Molecular abundance ratios are normalized to methanol and isomers are added because the ROSETTA mass spectrometer is not able to distinguish among them. Some molecular species, such as ethanol and dimethyl ether, show a striking agreement, within a factor of 10, suggesting chemical inheritance from the early stages. Measurements are from Rubin et al. (2019); Bianchi et al. (2017, 2019b, 2020); Bergner et al. (2019); Lee et al. (2019); Drozdovskaya et al. (2019); Taquet et al. (2015); López-Sepulcre et al. (2017).