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THE EARLY STAGE OF SOLAR-TYPE PROTOSTARS: THE MISSING EVIDENCE OF LARGE CARBON CHAINS

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Abstract. In the last few years a striking chemical diversity has been identified around Sun-like protostars. The vast majority of observations dedicated to the chemical exploration of these objects has been obtained via millimeter wavelength telescopes, where relatively light molecules, such as interstellar complex organic molecules or small carbon chains, have their peak of emission. In contrast, the lines of heavy molecules (e.g. chains and rings with more than seven C-atoms) at mm wavelengths are substantially weaker. Their observation would add a key piece to the overall puzzle as they might have a crucial role in the heritage of organic material from the pre- and proto- stellar phase to the objects of the newly formed planetary system, such as asteroids and comets. We report the first results obtained in a pilot study performed using the 100m Robert C. Byrd Green Bank Telescope (GBT) to observe several crucial C-bearing chains in the X and Ku bands (8–11.5 GHz and 14.0–15.4 GHz, respectively), in the two sources L1544 and IRAS16293-2422, which are considered the two archetypes of prestellar cores and protostars. This work paves the way for molecular exploration using SKA and it has inspired a new SKA user case, developed in the context of the Cradle Of Life working group activity.

Keywords: astrochemistry, star formation, large carbon chains

1 Introduction

The formation of a Solar-type planetary system starts with the collapse of a cold ($\leq$10 K) and dense ($\geq 10^5$ cm^{-3}) clump, called a prestellar core, in a molecular cloud. The evolution of the prestellar core into a protostar, a protoplanetary disk and, eventually, a planetary system, is also accompanied by the evolution of its chemical composition (e.g. Caselli & Ceccarelli 2012). Nowadays, we know that this evolution leads to protostars with a wide range of chemical composition, represented, for example, by hot corinos, which are enriched in interstellar complex organic molecules (hereinafter called iCOMs: e.g. Ceccarelli et al. 2007) and the WCCC (Warm Carbon Chain Chemistry) sources, which are enriched of unsaturated small carbon chains (fewer than about five C-atoms: e.g. Sakai & Yamamoto 2013). The origin of this chemical diversity is unclear and it may be related to environmental conditions at the epoch of icy dust mantles formation. (e.g. Sakai & Yamamoto 2013; Spezzano et al. 2017; Lefloch et al. 2018). Observational studies aimed at investigating the chemical inventories of Solar-type protostars have mainly been performed using (sub-)millimeter telescopes, where several relatively light molecules, like simple iCOMs or small C-chains, have their peak of emission. On the other hand, lines of heavy molecules (e.g. chains and rings with more than seven C-atoms) are quite weak at those wavelengths. For this reason, much less is known about the presence and evolution of heavy species. Even the relatively

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simple and abundant cyanotriacetylene (HC_7N) has only been detected in a handful of Solar-type prestellar cores and protostars (e.g. Gupta et al. 2009; Cordiner et al. 2012; Friesen et al. 2013; Jaber Al-Edhari et al. 2017). Yet, large C-carbon species might have a crucial role in the heritage of organic material from the pre- and proto- stellar phase to the objects of the newly formed planetary system, such as asteroids and comets (e.g. Mumma & Charnley 2011). Instructive results have been recently obtained towards the prestellar core TMC-1 by: (i) the GBT GOTHAM project (McGuire et al. 2020) and (ii) the Yebes QUIJOTE survey (Cernicharo et al. 2021). They reported the detection of cyclic hydrocarbons such as c-C_9H_8 (Burkhardt et al. 2021a) and o-C_6H_4 (Cernicharo et al. 2021). Interestingly, they also reported the detection towards different prestellar cores of benzonitrile (c-C_6H_5CN), suggesting that aromatic species are quite widespread at earlies stages (McGuire et al. 2018; Burkhardt et al. 2021a). In summary, these results confirm the presence of a complex carbon chemistry at work in Solar System precursors, calling for further observations of pre- and protostellar objects in different star forming regions. Despite the importance of large carbon species in the astrobiological context and its potential diagnostic power, only TMC-1 has been explored extensively so far. The present project fills this important gap in our knowledge, thanks to a survey of the archetype of prestellar cores and Class 0 protostars: L1544 and IRAS 16293-2422 (hereafter IRAS16293), respectively.

1.1 L1544 and IRAS 16293

L1544 (see e.g. the c-C_3H_2 map of Fig. 1) in the Taurus molecular cloud complex (d = 140 pc) is considered the prototype of prestellar cores, being on the verge of gravitational collapse (e.g. Caselli & Ceccarelli 2012). Its central high density ($\sim10^6$ cm^{-3}) and very low temperature ($\sim$ 7 K) trigger the peculiar chemistry typical of cold and CO depleted gas (e.g. Caselli et al. 1999). In the external layers, however, different rich chemical processes take place which lead to the formation of iCOMs and carbon chains (e.g. Bizzocchi et al. 2014; Vastel et al. 2016; Punanova et al. 2018). Indeed, recent (single-dish) IRAM 30-m observations in the mm-window show the presence of small carbon chains such as HC_3N, c-C_3H_2, C_3H, C_4H, C_2O and C_3O over extended portions of L1544 (see Fig. 1 Vastel et al. 2014; Spezzano et al. 2017; Urso et al. 2019).

IRAS16293 is a Solar-type protostar in the ρ Ophiuchus star-forming region (d = 120 pc). Given its proximity and relatively large envelope, it has been the target of numerous studies at mm and submm wavelengths that have revealed its physical structure. IRAS16293 possesses a large envelope that extends up to 6000 au (Castets et al. 2001; Crimier et al. 2010) and that surrounds two protostellar objects separated by 600 au (Mundy et al. 1992; Jørgensen et al. 2016). From a chemical point of view, the IRAS16293 envelope is composed of: (i) the outer cold ($\sim$ 10–30 K) envelope, characterized by the presence of cyanopolyynes (HC_3N, HC_5N, Jaber Al-Edhari et al. 2017) and small carbon chains (as in L1544) such as c-C_3H_2, C_2H, C_3H, C_4H (Caux et al. 2011), and emitting narrow lines (FWHM$\sim$ 1–2 km s^{-1}); (ii) the hot corino, where the abundance of many molecules (in particular iCOMs) increases by orders of magnitude (e.g. Ceccarelli et al. 2000; Coutens et al. 2012; Jaber et al. 2014; Jørgensen et al. 2016, 2018) due to protostellar heating, which reaches the sublimation temperature of the icy grain mantles ($\sim$ 100 K). While the hot corino has been the subject of a large number of (mainly interferometric) observations to infer its chemical composition (e.g. Lykke et al. 2017; Persson et al. 2018 and references therein), not so much has been done to study the chemistry of the cold outer envelope.

2 Observations and first results

The spectra observed with the GBT are shown in Fig. 2, where the rms is typically $\sim$ 1–2 mK in a channel of $\leq$ 0.1 km s^{-1}. Observations have unveiled many complex C-chain species (C_4H, C_6H, HC_7N, HC_9N, C_3S, Bianchi et al. in prep). Both L1544 and IRAS16293 were observed in Ku band, between 13.9 and 15.41 GHz (see Fig. 2, right panel). Successively, given the richness of the observed spectra, we followed up L1544 to cover the full X-band (8 – 11.5 GHz). The first immediate result is that there is a chemical diversity between L1544 and the envelope of IRAS16293, evident from the spectra reported in Fig. 2 (right panel). In particular, in IRAS16293 the detected molecular species are formaldehyde (H_2CO) and c-C_3H. Instead in L1544, we detected several bright emission lines from heavy carbon-chain molecules. More specifically, we detected several transitions of c-C_3H, C_4H, C_6H with associated hyperfine structure, HC_3N, HC_5N and HC_9N (see Fig. 1, right panel), H_2CO, CCS, and C_3S. All the lines are well detected with a high signal to noise (S/N between 3 and 40). The analysis to dermine the physical parameters of the emitting gas, as well as the molecular abundances towards the sources is in progress. Our findings can be considered as part of a community effort aimed at exploring the carbon-chain and aromatic chemistry at cm wavelengths using GBT in different objects (see e.g. GOTHAM and the forthcoming ARKHAM results; McGuire et al. 2020; Burkhardt et al. 2021b). An open question is now to understand wheather the non-detection of heavy carbon species towards IRAS16293 indicates a lack of these species in the gas phase or instead, that they are located in a compact region around the protostar (inner 100-200 au), thus being heavily diluted in the GBT beam. Despite the importance of such observations to unveil the chemical processes occurring at large angular scales, the major limitation is the lack of angular resolution of the single-dish telescope, which prevents us from exploring the planet formation regions. In this respect, the GBT pilot project has inspired a scientific use case for the SKA interferometer.

3 Beyond GBT: exploring the planet formation region with SKA

A fundamental step ahead in Astrochemistry will be to use the SKA to study the C-chain reservoir at small angular scales, where planetary systems are forming. Recently, a SKA use case dedicated to this topic has been developed in the context of the Cradle Of Life working group activity. In particular, the proposed project will shed light on the origin of the chemical diversity observed in Solar-System precursors and on how it affects the composition of the forming planetary systems, thanks to the combination of high angular resolution and sensitivity provided by SKA. The project will be highly complementary to several astrochemical surveys at mm- and submm- wavelengths, performed with IRAM-30m (e.g., ASAI survey; Lefloch et al. 2018), IRAM-NOEMA (e.g., SOLIS; Ceccarelli et al. 2017) and ALMA (e.g., PILS, Jørgensen et al. 2016; FAUST, Bianchi et al. 2020), which obtained the chemical census of complex organic molecules in Solar System precursors. In this respect, the SKA project represents a major step forward. On the one hand, it will overcome several limitations related to mm-observations, such as dust opacity and line confusion, providing new insights on the envelope/disk protostellar structure. On the other hand, it will unveil a new chemistry of complex C-chain species, expected to play a major role in the emergence of life, acting as the backbone of relevant biological molecules, such as proteins.

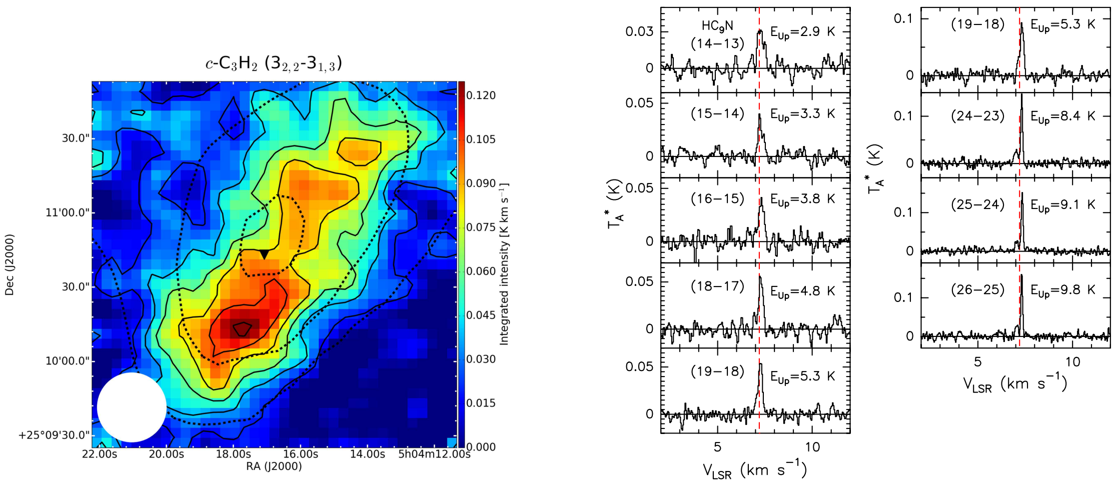

Fig. 1. Left: The prestellar core L1544 as observed with the IRAM 30-m (Spezzano et al. 2017). The map shows c-C_3H_2 integrated intensity emission at 3mm. **Right:** HC_9N transitions observed towards L1544 with the GBT. The vertical dashed lines mark the ambient LSR velocity (+ 7.2 km s^{-1}, Tafalla et al. 1998). The S/N is $\sim$ 15, and the lines are narrow with FWHM $\sim$ 0.08 km s^{-1}. The upper level energy of each transition is reported on the right inside each panel.

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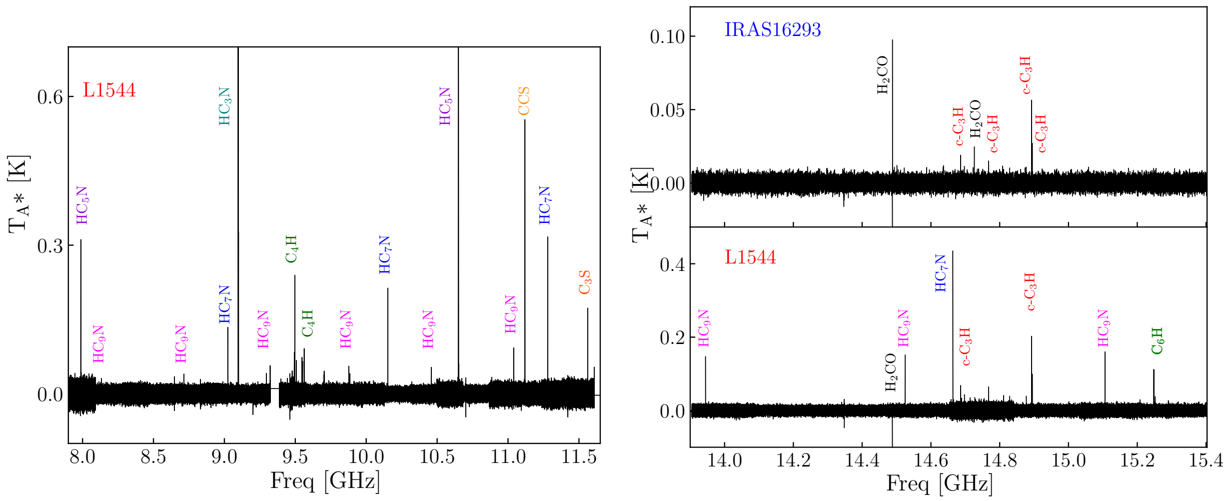

Fig. 2. Left: L1544 spectrum observed with the GBT in X-band. **R**ight: Spectrum observed with the GBT in Ku-band towars L1544 and IRAS16293-2224. The molecular species producing the emission lines are labelled in different colors. The y-axes is in antenna temperature.

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