HOT CORINOS: THE EARLY ORGANIC MOLECULAR ENRICHMENT OF THE PLANET FORMATION ZONES

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Abstract. The earliest phases of a planetary system formation are represented by young warm protostars. Therefore, characterize the chemical content of young protostars is a crucial point in retrieving our origins. There the dust gets warm enough to release the molecules on the icy mantles into the gas phase and trigger a complex chemistry creating the so-called hot corinos, rich in interstellar complex organic molecules (iCOMs). However, after almost twenty year of studies, very few hot corinos have been discovered, and many of them show very different molecular spectra at millimeter wavelengths. Two straightforward question arise: i) What is the origin and nature of hot corinos? ii) How are iCOMs synthesized? To answer these questions, I investigated the protostellar binary system NGC 1333 IRAS 4A and its surroundings. I used i) VLA centimeter wavelengths observations toward the two protostars to investigate their chemical nature and history and ii) high-angular resolution observations with NOEMA, as part of the SOLIS (Seeds of Life in Space) Large Program, to study the chemical complexity of their molecular outflows. This contribution reports the main findings of my PhD Thesis work, that received the PhD prize from the SF2A. It was carried out at IPAG in Grenoble and it was part of the project Dawn of Organic Chemistry (DOC), funded by the European Research Council (ERC) under the grant No 741002.

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1 Introduction

The formation of Solar-like stars goes through different stages, starting from a collapsing molecular core that evolves into a protostar, a protoplanetary disk, and eventually a planetary system. Together with the physical evolution, a chemical evolution takes place (see Figure 1.4)(Caselli & Ceccarelli 2012; Öberg & Bergin 2021). The discovery of iCOMs (interstellar Organic Molecules*, Herbst & van Dishoeck 2009; Ceccarelli et al. 2017) in the youngest phase of the formation of Solar-type stars, i.e., hot corinos (Ceccarelli 2004; Ceccarelli et al. 2007), raises a main important question: Is there a direct link between the first stages of Solar-like star formation and the latest ones? In other words, is the chemical complexity inherited from one stage to the other? Additionally, even though it has been thought for many years that the planets form in the protoplanetary disk stage (Class II, 10^7 yr), there have been recent evidences that shifted earlier the planet formation, already in the young protostellar stage (Class 0, 10^{4-5}yr) (Tychoniec et al. 2020; Sheehan & Eisner 2018; Segura-Cox et al. 2020). This enforces the importance of fully characterize, from a chemical point of view, the early stages of the formation of Solar-like stars, e.g., the protostellar one. However, protostars are really far to be chemically characterised.

2 Hot Corinos chemical diversity

The first sign of the presence of a rich organic chemistry in protostars comes in the early 2000 in the IRAS 16293-2422 source where abundant amounts of complex O- and N-bearing molecules were detected (Ceccarelli et al. 1998, 2000; Loinard et al. 2000; Cazaux et al. 2003). This was the first example of hot corino, a compact (< 100 au), hot (> 100 K), and dense (>10^7 cm^{-3}) region enriched in iCOMS, where the chemistry is dominated by the icy mantles sublimation. Since then, hot corinos were hunted at sub-mm wavelengths from single-dish to

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*interstellar Complex Organic Molecules: saturated C-bearing molecules with more than six atoms and containing heteroatoms.
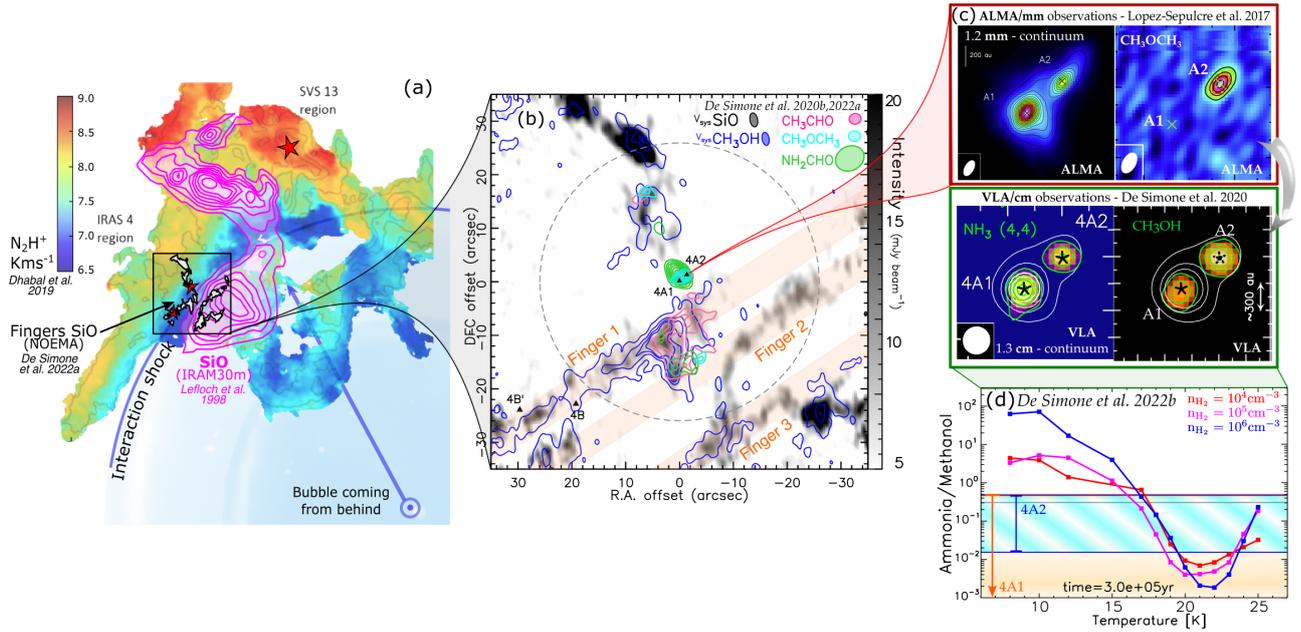
Fig. 1. *Panel (a)*: **NGC 1333 shaped by a clashing bubble.** N2H+ (1-0) velocity map of NGC 1333 south overlapped with SiO IRAM30m emission (magenta Dhabal et al. 2019; Lefloch et al. 1998), and SiO fingers (black De Simone et al. 2022). *Panel (b)*: **Outflows rich in iCOMs and shocks tracing external interaction.** iCOMs contour emission overlapped to SiO in greyscale in the IRAS 4A outflows observed with NOEMA/SOLIS (De Simone et al. 2020b, 2022). The shadowed area identify the three fingers. *Panel (c)*: **Hot corino obscured by mm dust.** IRAS 4A system observed in ALMA mm continuum (upper left) and mm lines (upper right) (López-Sepulcre et al. 2017), and with VLA NH$_3$ and CH$_3$OH lines (De Simone et al. 2020a; De Simone et al. 2022). *Panel d:* **The ice mantle history.** Theoretical prediction for NH$_3$/CH$_3$OH abundance ratio compared to the observed values (colored bands) (De Simone et al. 2022).

high sensitive interferometers, such us ALMA and NOEMA. However, after more than 20 years of search, only 25 iCOMs-rich hot corinos (40 with only CH$_3$OH) have been discovered (e.g., De Simone et al. 2017; Belloche et al. 2020; Bouvier et al. 2021; Yang et al. 2021). Additionally, several hot corinos in binary systems show very different millimeter molecular spectra (e.g., Yang et al. 2021; Codella et al. 2020b).

Several possibility may explain why hot corinos are so few and difficult to find, and why various protostellar system show such different molecular mm spectra: i) The dusty envelopes wrapping Class 0/I hot corinos could be optically thick enough to absorb the millimeter molecular lines and hide hot corinos. ii) Hot corinos are rare and the millimeter spectra reflect an intrinsic chemical diversity likely caused by a different history of the object. iii) the inner region is characterized by internal small scale substructures, such as disks, that can "protect" from the protostellar radiation. This implies that the temperature will drop not reaching the sublimation one, and the chemistry at play will change (Aikawa et al. 2020; Nazari et al. 2022; van Gelder et al. 2022).

Observational bias: The dust contribution

Several indirect evidences point that, at mm wavelengths, the dusty envelopes wrapping Class 0/I hot corinos could be optically thick (e.g., Miotello et al. 2014; Galván-Madrid et al. 2018; Galametz et al. 2019). Therefore, even if the mm wavelength is a perfect range to observe iCOMs thanks to the brightness of their emission, it can be not ideal to avoide optical thick dust effects. In order to test how much is the dust contribution at millimeter, me and my collaborators used a novel approach: we observed one of the simplest iCOMs, methanol (CH$_3$OH) at cm wavelength, with the JVLA interferometer, toward the IRAS 4A protostellar system, where only the source weaker in mm continuum, IRAS 4A2, shows mm iCOMs emission. We detected several methanol emission lines towards both sources with similar intensities (see Figure 1). With a non-LTE LVG analysis (Ceccarelli et al. 2003) we confirmed that methanol is tracing hot, dense gas in a compact region (about 70 au). Therefore, also IRAS 4A1, the source that at mm-wavelength lacks in iCOMs emission, has a hot corino region that was obscured by the thick mm dust. Additionally, we raised an important warning: the dust is affecting also the emission of IRAS 4A2, the known hot corino. Indeed, at 143 GHz we estimated a dust absorption of about

30%. That means that all the iCOMs abundances derived at mm wavelengths need to be taken with caution (De Simone et al. 2020a).

The protostellar ice mantle history

With these results we demonstrated that hot corinos can be few because hidden by the dust at mm wavelength. However, different hot corinos can still have different spectra. It is then crucial to measure the chemical composition of the ice mantles formed in the previous prestellar core phase to understand the chemical reservoir available for hot corinos. However, the direct study of the ice mantle composition in these young embedded sources is challenging. A possibility is to retrieve it indirectly by observing the ice mantle species when they are released in the gas phase in hot corinos. Among the major ice mantle species (Boogert et al. 2015; McClure et al. 2023), the critical tracers in the gas phase are NH_3 and CH_3OH, as they can be simultaneously observed with ground base telescope (JVLA), they can trace only the inner hot corino region, and they have very well known formation paths (Watanabe & Kouchi 2002; Rimola et al. 2014; Le Gal et al. 2014; Song & Kästner 2017; Tinacci et al. 2022). Aa a consequence, the NH_3/CH_3OH abundance ratio depends on the cloud temperature and density, and on the ice mantle formation timescale (Taquet et al. 2012; Aikawa et al. 2020).

Using JVLA we detected several lines of both CH_3OH and NH_3 toward the binaries IRAS 4A1 and 4A2, and IRAS 4B located 30" away from the binary. Using a non-LTE LVG analysis (Ceccarelli et al. 2003), as described in (De Simone et al. 2022), we derived the physical properties of the gas assessing that both species trace the hot corino region, and we derived their abundance ratio. Surprisingly, the three protostars show similar NH_3/CH_3OH value, that means that they went through the same chemical history. In other words, they were formed from a pre-collapse material with similar physical conditions. To quantify these physical conditions we run an astrochemical model (`grainoble;` Taquet et al. 2012; Ceccarelli et al. 2018) predicting the species abundance at different timescales, temperatures and densities of the pre-collapse material. Then we compared the predictions with the observations (Figure 1) and we found that to reproduce the observations, at the time of the icy mantle formation, the pre-collapse material should have been at about 17 K. However, at 70 au scales one would expect much lower temperature in a prestellar core (around 7 K Crapsi et al. 2007). On the other hand, the large- scale maps of Herschel-Planck (Zari et al. 2016) show that the average dust temperature of the south part of NGC 1333 is around 17 K. We then suggested that the three protostars did not have the usual dense and cold precollapse phase, as their mantles were mostly built during a relatively warm phase (dust temperature $\sim$17 K), which is characteristic of the less dense cloud material in NGC 1333 South (De Simone et al. 2022). In other words, something must have triggered a fast collapse and the protostars' formation.

3 The importance of the environment: outflows and shocks

The IRAS 4 protostars are located in the Perseus/NGC 1333 molecular cloud. As many star forming regions NGC 1333 is associated with filamentary structures, probably shaped by external triggers. In particular, the southern part, where IRAS 4 lie, show a clear velocity gradient blueshifted at the bottom and redshifted at the top (Figure 1) (e.g., Dhabal et al. 2018, 2019). Dhabal et al. (2019) hypothesized that this gradient could be due to a colliding "turbulent cell", a clash that could have triggered the birth of the protostars. However, no specific signatures of a clash, namely shocks, have been reported so far, leaving unanswered how and where the energy of this clash, if real, is dispersed.

Constraining iCOMs formation routes in molecular outflows

Using NOEMA observations from the SOLIS Large Program (Ceccarelli et al. 2017), I imaged the large scale (about 50", 15000 au) around the IRAS 4A protostars. The high angular resolution and high sensitivity observations allowed us to detect and image, for the second time ever after L1157-B1 (Codella et al. 2017, 2020a), several interstellar Complex Organic Molecules (iCOMs) in the IRAS 4A outflow (Figure 1): methanol tracing the whole lobes of the two outflows, acetaldehyde bright in the south-east lobe, dimethyl ether and formamide showing compact emission [4]. Analyzing the emission in different positions of the outflows, and focusing on methanol and acetaldehyde, we confirmed the presence of chemical differentiation, with the southeast lobe (driven by 4A1) brighter in iCOMs than the southwest-north (driven by 4A2). As explained in full details in De Simone et al. (2020b), comparing the observations with astrochemical model predictions we could test the formation path of acetaldehyde suggesting that it is synthesized in the gas phase by the reaction of atomic oxygen with ethyl radical.

Train of shocks as a signature of an unexpected clash

While analyzing the methanol emission in the IRAS 4A outflows, we noticed the presence of an elongated structure almost perpendicular to the outflow with a narrow spectral profile (FWHM$\sim$1.5 km s^{-1}) peaking at the systemic velocity of the cloud. Similar structures were observed in SiO by Choi (2005) with the VLA, and by Lefloch et al. (1998) and Codella et al. (1999) with the IRAM 30m as a widespread SiO emission with unknown origin. To understand if these features were related, we analyzed the NOEMA/SOLIS observations of CH_3OH and SiO. We identified three parallel fingers separated by about 10" ($\sim$3000 au), and chemically different with the northern Finger1 traced by both species, and the other two fingers traced only by SiO (in agreement with Choi 2005). Additionally the fingers are located in the large-scale blueshifted southern region of NGC 1333 (see Figure 1). Analyzing the methanol and SiO emission using a non-LTE LVG analysis (Ceccarelli et al. 2003) as described in (De Simone et al. 2022), we derived the gas properties and the SiO/CH_3OH abundance ratio in the fingers. We confirmed the observed chemical diversity, and we found that they are tracing high density ($> 10^5$ cm^{-3}) and high temperature (>80 K) material. However, what is their origin?

We investigated two possibilities: the fingers are tracing i) Kelvin Helmholtz instabilities or ii) a train of shocks. However, even if the former could reproduce the quasi periodicity of the fingers, it could not reproduce the observed gas density and temperature. Therefore, the only plausible possibility was a train of shocks, well justified by the presence of both SiO and methanol, known shock tracers (e.g., Bachiller et al. 1998, 2001; Arce et al. 2008; Codella et al. 2012), and by the derived gas physical condition. Comparing the observed CH_3OH/SiO abundance ratio with astrochemical model predictions we put constraint on when the shocks occurred in order to explain the observed chemical differentiation. We suggested that the northern finger is the youngest one and it happened at least 5000 yr after the next southern one. Therefore the three fingers could be the result of a successive train of shocks created by the clash of an expanding bubble coming from south-east and moving towards the IRAS 4A main cloud from behind (De Simone et al. 2022). Finally, we suggest that the widespread narrow SiO emission observed towards the NGC 1333 IRAS 4 and SVS 13 region with single-dish observations in the late 1990s (Lefloch et al. 1998; Codella et al. 1999) is due to unresolved trains of shocks like the SOLIS fingers. These shocks would be the signature of the interaction of the bubble giving rise to the IRAS 4A fingers and maybe the same bubble triggered prematurely the formation of the protostars in the filament, as suggested by the results on study of the ice mantle composition (as reported in Section 2; De Simone et al. 2022).

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