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Multi-line Diagnostics of the Interstellar Medium

Interstellar complex organic molecules in the prototypical Class I protostar SVS13-A: From large scales to planet forming disks

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Abstract. We present a chemical systematic study of the Class I object SVS13-A obtained in the framework of two IRAM Large Programs: ASAI (Astrochemical Survey At IRAM-30m) with the 30m and SOLIS (Seeds Of Life In Space) with NOEMA. Thanks to the ASAI high-sensitivity unbiased spectral survey of the 3, 2 and 1.3mm bands, we detect and analyse several emission lines from deuterated species and interstellar complex organic molecules (iCOMs, e.g. molecules composed by 6 or more atoms and based on carbon). Within SOLIS, we obtain high-sensitivity and high-spatial resolution ($\sim$ 180 au) maps of crucial iCOMs. As a follow up, thanks to ALMA we explore the chemistry in the planet forming region ($\sim$ 50 au). We image emission lines from methanol (CH_3OH), acetaldehyde (CH_3CHO), formamide (NH_2CHO) and dimethyl ether (CH_3OCH_3). The different spatial distributions suggest a chemical differentiation inside the binary system or a different continuum opacity in the two protostellar disks.

1 Introduction

Evidence is mounting that planet formation in Sun-like protostars may already start during the early Class I phase (age $< 10^5$ years). Indeed, recent observations have shown the presence of substructures such as gaps and rings in very young protostellar disks [e.g. 12]. Moreover, evolved Class II disks are not enough massive to explain the observed exoplanets population, in contrast to early Class 0 and I disks [13]. While close to the protostar a chemical reset is expected, in the outer protostellar disk a consistent part of the molecular complexity is expected to be inherited from the early stages [e.g. 11]. In this respect, observations of protostars in the early Class I stage are crucial to investigate the initial chemical budget of the forming planetary systems.

2 SVS13-A: A chemically rich Class I hot corino

SVS13-A is a very well studied Class I protostar, located in the NGC1333 star forming region in Perseus (at a distance of about 300 pc). The source drives a large-scale outflow and the HH7–11 Herbig-Haro chain [8, 9]. From VLA observations SVS13-A is known to be a close binary, with a separation of $0\farcs3$. SVS13-A has been the target of several observational

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large programs dedicated to explore its molecular complexity. The first one was ASAI[1] [10], an unbiased spectral survey performed with the IRAM-30m which disclosed the presence of a hot corino chemistry towards the source with the detection of several iCOMs, such as methanol and its isotopologues (CH_3OH, $^{13}CH_3OH$, CH_2DOH), acetaldehyde (CH_3CHO), methyl formate ($HCOOCH_3$), dimethyl ether (CH_3OCH_3), glycolaldehyde ($HOCH_2CHO$), formamide (NH_2CHO), ethanol (CH_3CH_2OH), and water (HDO) [2, 5].

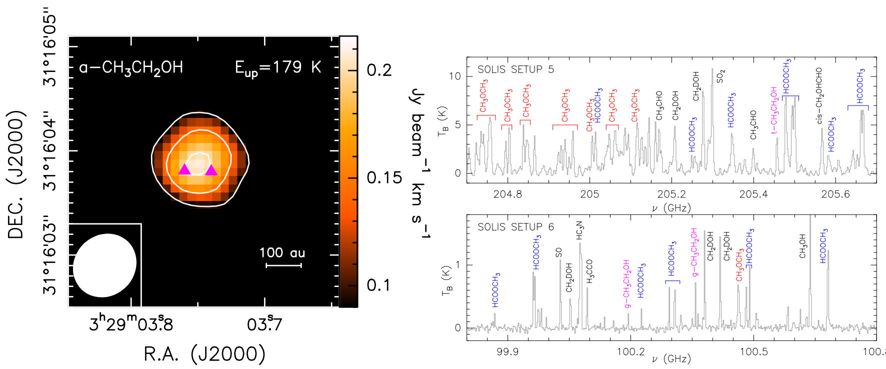

Figure 1. Molecular complexity towards SVS13-A, as observed by the NOEMA SOLIS Large Program. On the left, a map of CH_3CH_2OH emission. On the right, spectra extracted towards the source peak position showing emission from iCOMs.

The hot corino has been successively imaged with the NOEMA interferometer in the framework of the CALYPSO [1] and SOLIS[2] (Seeds Of Life in Space; [4]) large programs. Figure 1 shows a map of ethanol emission obtained by SOLIS as well as some spectra extracted towards the source position, showing the rich chemical complexity observed in SVS13-A. More specifically, the broad spectral coverage provided by the IRAM PolyFiX correlator, allowed the detection of more than 100 emission lines from iCOMs. This was crucial to obtain a proper line identification, as well as a precise determination of the gas physical parameters, such as the rotational temperatures and the column densities. Despite the good angular resolution of the NOEMA interferometer (0.″6, 180 au at 1.4mm), iCOMs emission was unresolved towards this close binary system. The position of the two components is shown by pink triangles in Figure 1. In order to resolve the emission in the planet-forming region (∼ 50 au), we performed complementary ALMA Cycle 6 high-angular resolution observations.

3 SVS13-A: Exploring the planet-forming region

We observe SVS13-A in ALMA Band 6 with a synthesized beam of 0.″2 × 0.″13 [3], clearly resolving the binary system. The dust emission shows the presence of two possible circumstellar disks as well as several circumbinary structures (see Fig. 2). Performing different beam tapering, we were able to confirm that these structures are real and not related to the beam elongation in the N-S direction. We performe a *uv* plane fitting analysis of the continuum emission and we obtain a beam deconvolved sizes of 180 × 70 au (VLA4A), and 90 × 70 au (VLA4B), for the protostellar disks. From the molecular line emission we derive

[1] https://www.oan.es/asai/
[2] https://solis.osug.fr/

systemic velocities of +7.7 km s^{-1} and +8.5 km s^{-1} for VLA4A and VLA4B, respectively. The moment 1 maps reveal blue-red rotation, roughly perpendicular to the outflow direction.

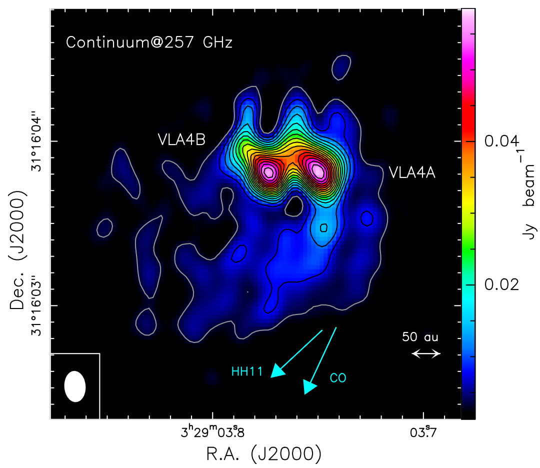

Figure 2. The planet-forming region (~ 50 au scale) of the SVS13-A as observed by ALMA (from [3]). The dust continuum emission at 257 GHz shows two protostellar disks and accretion streamers.

We observe several transitions from iCOMs. More specifically, we detected 3 lines of methanol and 5 of $^{13}CH_3OH$, 2 lines of acetaldehyde, 4 lines of dimethyl ether and 3 of formamide, covering a broad range of upper level energies (up to 800 K). The molecular emission is resolved towards the binary system and shows a very complex structure. Figure 3 shows the comparison between one line of NH_2CHO and one line of CH_3OCH_3. The maps show that formamide emission is more concentrated towards VLA4A, while dimethyl ether emits towards both the protostars. A similar behaviour is observed for acetaldehyde and methanol. We perform a non-LTE large velocity gradient analysis of the methanol lines and we derive kinetic temperatures of 140 and 170 K for VLA4A and VLA4B, respectively and gas densities larger than 10^7 cm^{-3} indicating that lines are LTE populated. We assume the derived temperatures to calculate the iCOMs column densities in VLA4A and VLA4B, under LTE conditions. The chemical differentiation between VLA4A and VLA4B is evident when considering the column density ratios which are > 4 for NH_2CHO and between 1–3 for the other O-bearing species. Moreover, the iCOMs emission is partially elongated towards the north, being spatially coincident with the streamers seen in the continuum.

The observed chemical segregation is independent from the transition upper level energy, thus it is very likely not related to different excitation effects. One possibility is that the chemical differentiation is related to O-bearing and N-bearing species. However, the detection of ethylene glycol only emitting from VLA4A was recently reported [7], questioning this hypothesis. A second possibility is that the chemical differentiation is a result of the combined effect of continuum opacity and different iCOMs binding energies. Indeed, continuum opacity can hamper iCOMs detection at mm wavelengths [6]. If we assume that the different molecules are emitted in a larger or more compact region they could be more or less affected by the continuum opacity. To test this scenario we perform new quantum chemistry computations to evaluate the binding energies of formamide and ethylene glycol, which are the two species so far detected only towards one component of the binary system. Their high binding energies suggest that they are emitted in a compact region around the protostar, more compact that the emitting region of methanol or dimethyl ether. This would imply that they

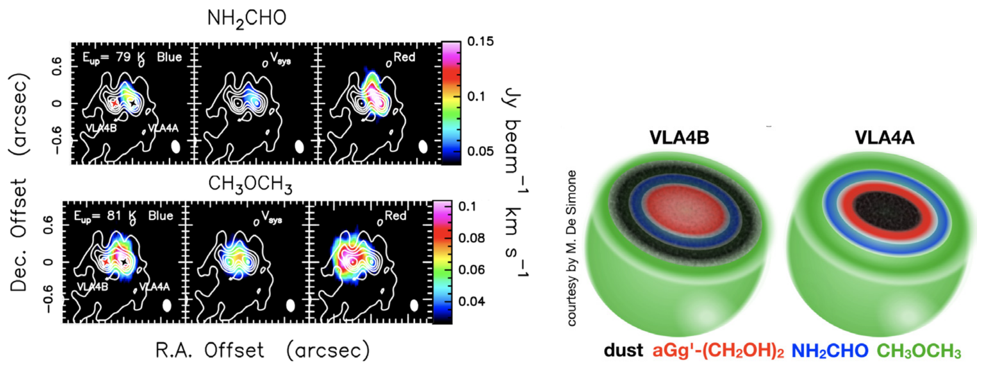

Figure 3. *Left panel:* Integrated emission of NH_2CHO and CH_3OCH_3, in color scale, superposed on the dust emission in white contours (adapted from [3]). *Right panel:* Sketch illustrating the combined effect of dust opacity and different iCOMs binding energies.

are completely obscured by the dust in VLA4B where the dust is very optically thick while they are still visible in VLA4A, where the dust is less optically thick (see the sketch in Fig. 3, right panel).

4 Conclusions

Class I protostellar disks are the birth places of planets and it is crucial to investigate their chemical composition in order to understand the initial conditions of planets formation. In particular, broad spectral surveys and high angular resolution observations are highly complementary to study the chemistry of protostellar disks. Thanks to the synergy between the IRAM and ALMA telescopes, we investigate the chemistry of the Class I source SVS13-A from the large scales to the planet formation region (∼ 50 au). We observe in the continuum two protostellar disks and accretion streamers, in addition to several emission lines from iCOMs. We observe a chemical segregation between the two components of the binary system. We interpret this chemical differentiation as the result of the combined effect of dust opacity and different binding energies.

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