On-going gas-phase organic chemistry observed through the emission of CH^+ and CH_3^+ in the Orion Bar

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CH^+ and CH_3^+ are key molecules in the gas-phase organic chemistry and are thought to be important intermediate to the formation of a variety of carbonaceous species. The study of these molecules is essential to understand the complex chemistry happening in star and planet-forming regions. However, their emission in the infrared is very faint and has only been made possible thanks to the very high angular resolution and high sensitivity of the James Webb Space Telescope (JWST).

Recent observations with the ERS 1288 program "PDR4ALL" (Berné et al. 2022, Habart et al. 2023, Peeters et al. 2023) have provided imaging and spectroscopy of the Orion Bar in the prototypical highly irradiated dense PDR and externally irradiated disks (disk d203-506).

In this contribution, I will present the first NIRSpec and MIRI detection of vibrationally excited CH^+ and CH_3^+ in the Orion Bar. Following the study on OH emission in d203-506 (Zannese et al. 2024), I will show how these emissions can probe the on-going chemistry in this region and how one can derive the formation rate of highly excited molecules directly from observed intensities. I will highlight the importance of these diagnostics as these molecules are expected to be detected in various environment such as other disks and high- and low-mass star forming regions. In particular, I will show how to leverage the high spatial and good spectral resolution of NIRSpec and MIRI to resolve the spatial distribution of these excited species and conduct detailed analysis of their excitation. CH^+ and CH_3^+ are indeed detected in very different environments throughout the Orion Bar, both in the disk d203-506 (Berné et al. 2023) and the interstellar PDR (Zannese et al. in prep). The spatial correlation between the ro-vibrational lines of these molecules and H_2 revealed by the observations and study of their excitation are in favor of CH^+ (resp. CH_3^+) being formed and chemically pumped by the reaction $C^+ + H_2$ -> $CH^+ + H$ (resp. $CH_2^+ + H_2$ -> $CH_3^+ + H$). These results shed light on the gas-phase route of carbonaceous species with successive reaction with H_2 : $C^+ \rightarrow CH^+ \rightarrow CH_2^+ \rightarrow CH_3^+$. In the case of CH^+, where the state-to-state data are available, I will show the good agreement between quantum dynamical models of chemical pumping and observations. This excitation at the formation process has already been observed in the ro-vibrational emission of OH (Zannese et al. 2024).

These micro-processes allow us to put strong constrains on those strongly irradiated environments, on density and formation rate for instance. Thus, I will highlight the need for new quantum calculations to build state-to-state astrochemical models in the JWST era.

Zannese, M. et al., OH as a probe of the warm-water cycle in planet-forming disks, *Nature Astronomy* (2024)

Berné, O., Habart, E., Peeter, E. et al., PDRs4All: A JWST Early Release Science Program on Radiative Feedback from Massive Stars, *PASP*, **134**, 054301 (2022)

Habart, E. et al. PDRs4All II: JWST's NIR and MIR imaging view of the Orion Nebula. *arXiv e-prints* (2023)

Peeters, E. et al. PDRs4All III: JWST's NIR spectroscopic view of the Orion Bar. *arXiv e-prints* (2023)

Berné, O. et al. A far-ultraviolet-driven photoevaporation flow observed in a protoplanetary disk, *Science* (2024)