Abstract

Unraveling the non-equilibrium chemistry of the temperate sub-Neptune K2-18 b.

A. Y. Jaziri[1,2], O. Sohier[1], O. Venot[3] and N. Carrasco[1,4]

[1] LATMOS/IPSL, UVSQ Universit Paris-Saclay, Sorbonne Universit, CNRS, Guyancourt, France.
[2] Laboratoire dastrophysique de Bordeaux, Univ. Bordeaux, CNRS, B18N, allée Geoffroy Saint-Hilaire, 33615 Pessac, France
[3] Université Paris Cité and Univ Paris Est Creteil, CNRS, LISA, F-75013 Paris, France
[4] ENS Paris-Saclay, Université Paris-Saclay, Gif-sur-Yvette, 91190, France

The search for habitable, Earth-like exoplanets faces significant observational challenges due to their small size and faint signals. M-dwarf stars provide an opportunity to detect and characterize smaller planets, particularly sub-Neptunes, which are among the most common exoplanetary types. K2-18 b, a temperate sub-Neptune in the habitable zone of an M-dwarf star, has been studied using HST and JWST, revealing an H_2-rich atmosphere with detected CH_4 and possible CO_2. However, previous debates in atmospheric composition, emphasize the importance of non-equilibrium chemistry models. These models are crucial for interpreting exoplanetary atmospheres, constraining key parameters such as metallicity, C/O ratio, and vertical mixing (K_{zz}), and assessing the potential for prebiotic chemistry.

This study aims to comprehensively explore the parameter space of metallicity, C/O ratio, and K_{zz} for K2-18 b using the non-equilibrium chemical model *FRECKLL* in conjunction with JWST observational data. By refining these constraints, we seek to improve our understanding of the planets atmospheric composition, detect minor species, and assess the potential for prebiotic chemistry in a temperate sub-Neptune within the habitable zone of an M-dwarf star. Our approach involves running non-equilibrium chemical models across a three-dimensional parameter space (metallicity, C/O ratio, and K_{zz}), generating the corresponding theoretical spectra, and comparing these spectra to JWST observational data to refine atmospheric constraints.

We retrieved a best-fit atmospheric model for K2-18 b favoring high metallicity (255^{+303}_{-93} at 2σ) and a high C/O ratio (C/O $\geq$ 2.07 at 2σ). CH_4 is robustly detected ($\log_{10}[CH_4]$ = $-0.4^{+0.2}_{-1.6}$ at 1mbar), while CO_2 and other species remain uncertain due to observational noise and spectral overlap. The eddy diffusion coefficient (K_{zz}) has no significant impact on the fit and remains unconstrained. Non-equilibrium models exceed 4σ confidence over a flat-line which validates the presence of atmospheric features. Several minor species, including prebiotic molecules, may exist at ppm levels, though their features are likely masked by dominant species.

We used non-equilibrium chemical models and JWST data to investigate the atmosphere of K2-18 b, revealing a high metallicity, a high C/O ratio and complex chemical composition. While CH_4 is robustly detected, CO_2 remains uncertain, and minor species like H_2O and NH_3 are likely present. A lower limit on the C/O ratio is constrained, though no upper limit is established. The high C/O ratio also suggests a higher probability of aerosol formation. Our findings highlight the limitations of traditional retrievals with constant abundances and the importance of non-equilibrium models. Although equilibrium models can reproduce the data, physical conditions indicate that the atmosphere is in a non-equilibrium state, highlighting the limited constraints from current observations and the pressing need for improved data. Future observations with JWST NIRSpec G395H and ELT/ANDES will be key to refining atmospheric constraints and probing potential habitability.