Mario Basilicata
Tor Vergata University of Rome
mario.basilicata@inaf.it
LinkedIn:

Multiple molecular species in the atmosphere of the warm-Neptune HAT-P-11 b at high resolution

Mario Basilicata[1,2], Paolo Giacobbe[2], Aldo Stefano Bonomo[2], Matteo Brogi[3,2], Luigi Mancini[1,2,4], Alessandro Sozzetti[2]

[1]Department of Physics, University of Rome "Tor Vergata", Rome, Italy;
[2]INAF – Astrophysical Observatory of Turin, Pino Torinese, Italy;
[3]Department of Physics, University of Turin, Turin, Italy;
[4]Max Planck Institute for Astronomy, Heidelberg, Germany.

Overview

The aim of this work is to probe the atmospheric composition of the warm-Neptune HAT-P-11 b through near-infrared (NIR) high-resolution transmission spectroscopy, as part of the Global Architecture of Planetary Systems (GAPS) project.
The study of exoplanetary atmospheres makes a crucial contribution to the exoplanet characterisation process. For example, by knowing the chemical composition of the primary atmosphere of an exoplanet, it is possible to constrain its formation and evolution path based on the study of relative elemental abundances. High-resolution ($R \geq 25.000$) spectroscopy from ground-based instruments [1] can give important information about the thermo-chemical structure and the dynamics of exo-atmospheres, since it allows to spectrally resolve single absorption/emission lines and to measure their Doppler shift. The atmospheric characterisation of hot and warm Neptune-size exoplanets is challenging due to their relatively small radius and atmospheric scale height but the warm-Neptune HAT-P-11 b is a remarkable target because of the large brightness of its host star (V = 9.46 mag; H = 7.13 mag).
Analysing four transits observed with the GIANO-B high-resolution spectrograph (wavelength range: 0.95-2.45 μm, spectral resolving power: 50.000), mounted at the Telescopio Nazionale Galileo (TNG), we detect the presence of H_2O and NH_3 and tentatively detect CH_4 and CO_2 in the atmosphere of this target [2].
This result constitutes the first multiple molecular species observation in the atmosphere of a warm-Neptune planet at high resolution.

1. Data reduction

We extracted the spectra with the Gofio pipeline [3] and re-fined the wavelength calibration using the position of telluric lines. The telluric and stellar contamination were removed with a principal component analysis (PCA), following the methods explained in Giacobbe et al. 2021 [4].

The residuals were cross-correlated with single-species template transmission spectra built with PetitRADTRANS [5] (isothermal profile at T_{eq}=699 K, VMR_{H_2} = 0.855, VMR_{He}= 0.145, $VMR_{molecule}$= 10^{-3}), for 8 molecular species (H_2O, CH_4, NH_3, C_2H_2, HCN, CO, CO_2, H_2S).

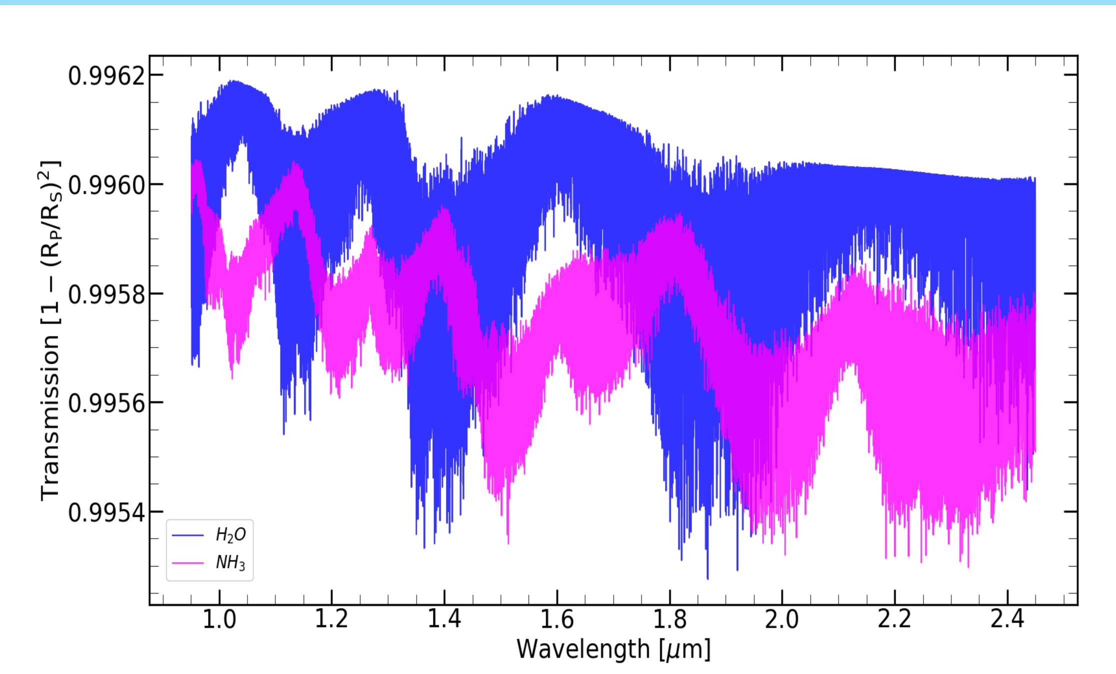


Fig. 1. Example of template transmission spectra built with PetitRADTRANS, in the GIANO-B wavelength range.

2. Search for a detection

We shifted the cross-correlation function (CCF) values into the planetary rest-frame and summed them in phase, testing different trial planetary radial-velocity semi-amplitudes (K_p), obtaining the K_p-V_{rest} maps.
The S/N was calculated by dividing the CCF values by the standard deviation of the noise far from the peak ($|V_{rest}| \geq 25$ km/s).

We identify a signal with S/N ≥ 3 around the expected K_p-V_{rest} position for four chemical species (potential detections): H_2O, CH_4, NH_3 and CO_2.

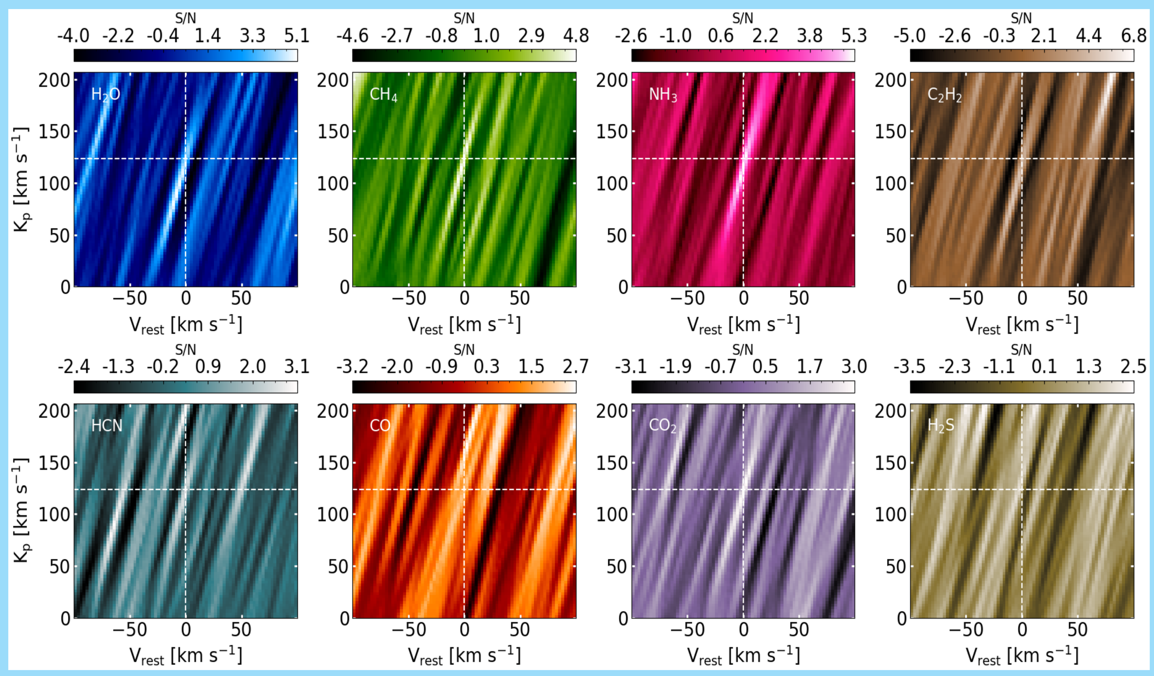
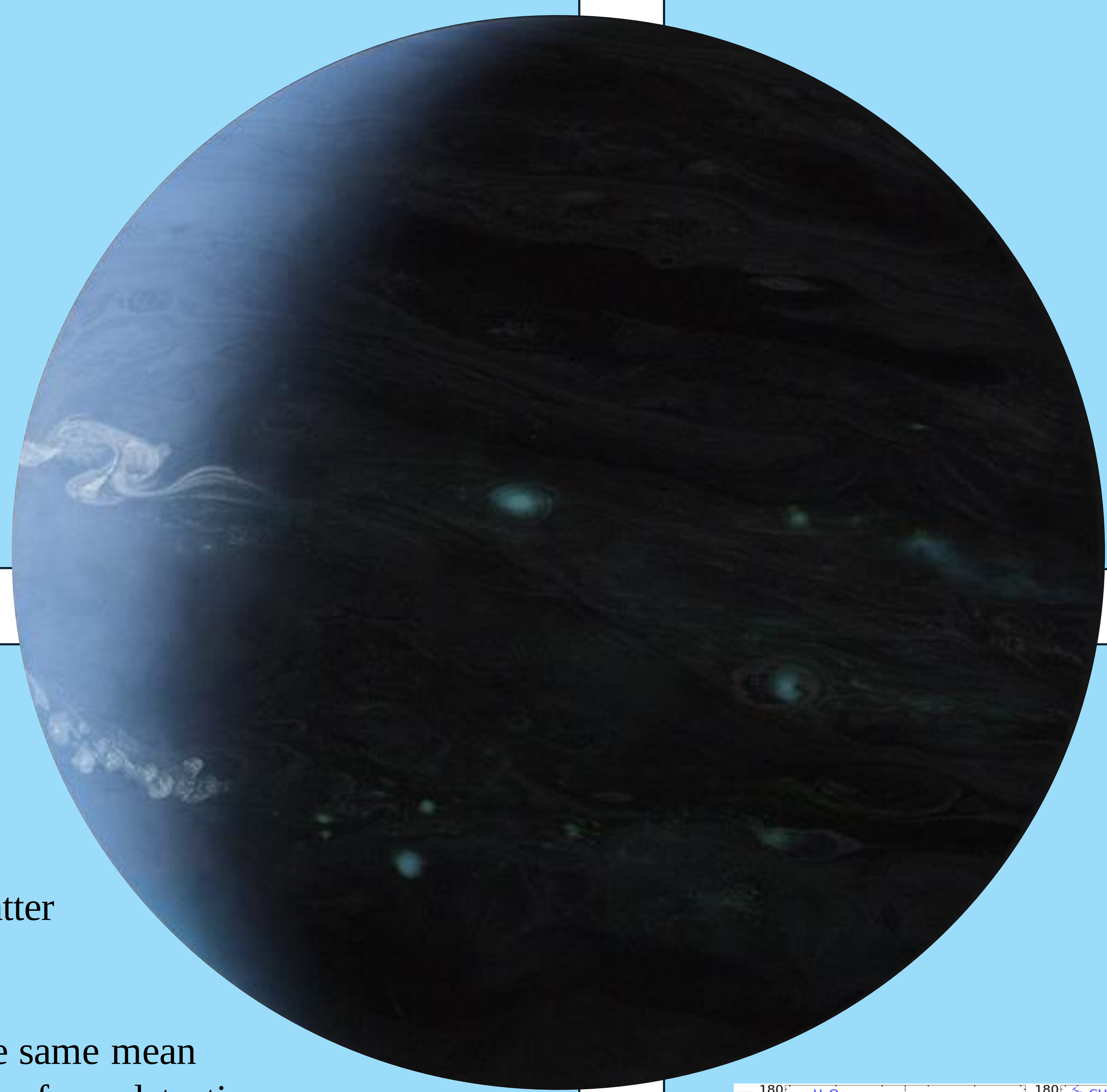


Fig. 2. S/N K_p – V_{rest} maps for the 8 probed molecular species.



3. Estimate the significance

The significance (σ) of the detections was estimated from a Welch *t-test* on 2 samples of CCF values: the former far ($|V_{rest}| \geq 25$ km/s) from the planet's rest-frame velocity and the latter around it ($|V_{rest}| \leq 3$ km/s).

The test rejects the null hypothesis that the two samples have the same mean at a certain significance level that we adopted as the significance of our detections.

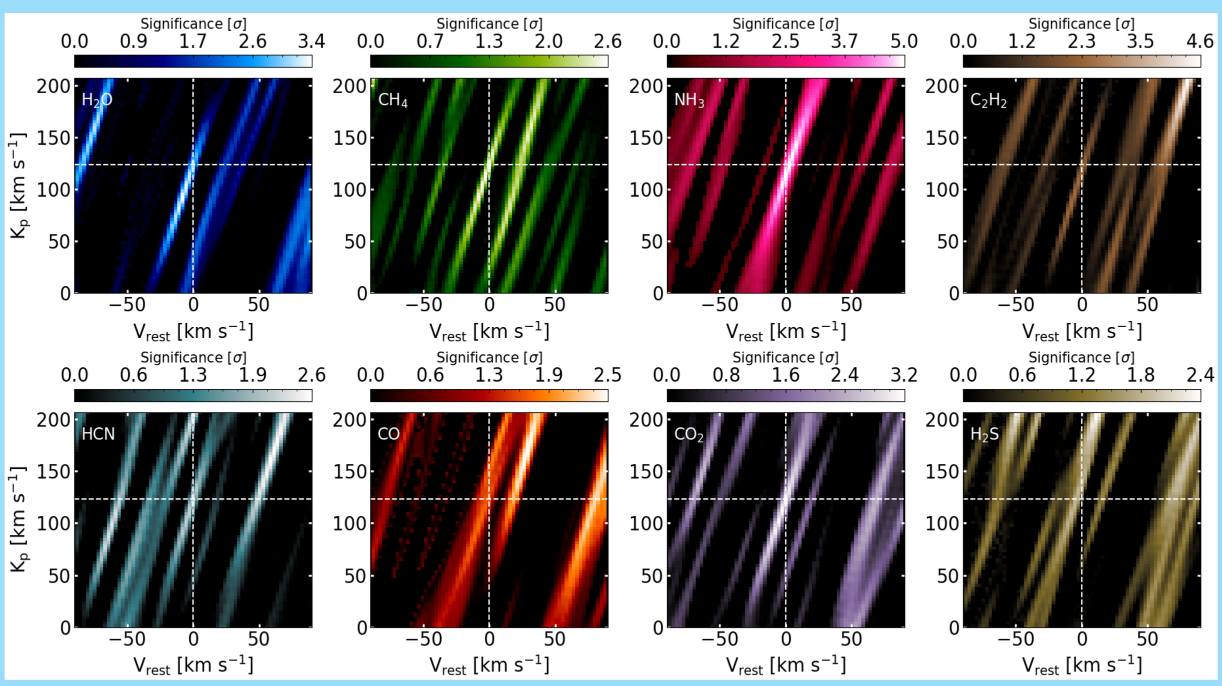


Fig. 3. Significance K_p – V_{rest} maps for the 8 probed molecular species.

4. Test the robustness of the results

Focusing only on the four chemical species whose signal had a significant peak around the expected position in the maps, we performed different tests to assess the robustness of our results before claiming a detection.
Among these tests:

- we computed the compatibility of the Doppler shift of the signals with the planetary radial-velocity;
- we computed the probability (*p-value*) that our results were due to a possible time-correlated noise, by randomly shuffling the CCF values as a function of the orbital phase 250 times and analysing the S/N and σ values obtained in the resulting K_p-V_{rest} maps.

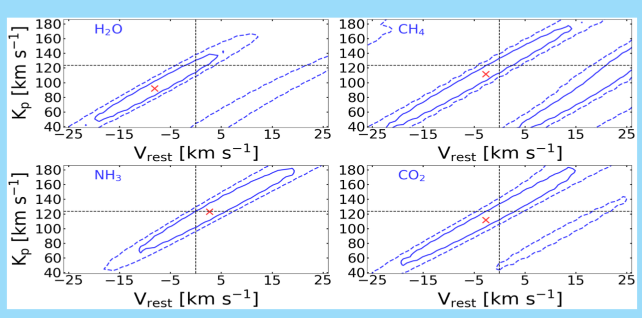


Fig. 4. Contour plots of the detection significance for the four chemical species of interest.

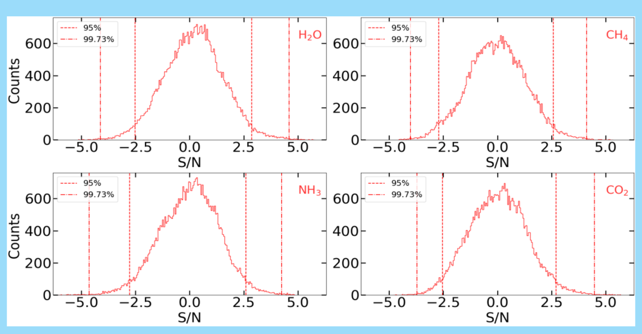


Fig. 5. Distribution of S/N obtained by shuffling 250 times the time order of the observed spectra, for each of the four chemical species of interest.

Molecule	S/N	Welch t-test Significance	Planetary RV Compatibility	p-value S/N	p-value σ t-test	Status$^{(a)}$
H_2O	5.1	3.4 σ	<1 σ	0.046%	1.3%	*D*
CH_4	4.8	2.6 σ	<1 σ	0.023%	3.8%	*TD*
NH_3	5.3	5.0 σ	<1 σ	0.039%	0.011%	*D*
CO_2	3.0	3.2 σ	<1 σ	2.5%	1.3%	*TD*

Conclusion

- We confirm the presence of H_2O (S/N = 5.1, 3.4 σ) already detected at low resolution [6] and detect the presence of NH_3 (S/N = 5.3, 5.0 σ) in the atmosphere of HAT-P-11 b.
- We also tentatively detect CH_4 (S/N = 4.8, 2.6 σ) and CO_2 (S/N = 3.0, 3.2 σ), whose presence needs to be confirmed by further studies.
- Next step: perform atmospheric retrievals in a Bayesian framework to study the physical and chemical properties of the atmosphere (e.g., *T-P* profile, chemical abundances, C/O).

Scan this QR code to read the full article!

References:
[1] Birkby, J. L., 2018 (Springer International Publishing AG), doi: 10.1007/978-3-319-55333-7_16
[2] Basilicata, M., et al. 2024 (A&A, 686, A127), doi: 10.1051/0004-6361/202347659
[3] Rainer, M., et al. 2018 (Proc. SPIE 10702, 1070266), doi: 10.1117/12.2312130
[4] Giacobbe, P., et al. 2021 (Nature, 592, 205), doi: 10.1038/s41586-021-03381-x
[5] Mollière, P., et al. 2019 (A&A, 627, A67), doi: 10.1051/0004-6361/201935470
[6] Fraine, J., et al. 2014 (Nature, 513, 526), doi: 10.1038/nature13785