The Solar System planets as testing ground for exoplanets: a contribution from the Ariel Consortium Working Groups

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Introduction: Several science Working Groups (WG) were formed in 2019 within the Ariel Mission Consortium to help prepare the RedBook (Tinetti et al. ESA/SCI(2020)1), defining the science cases, and to contribute to address three fundamental questions 1) what exoplanets are made of; 2) how they formed and 3) how they evolve. Among those WGs, "*Synergies between Solar System planets and exoplanets*" was set-up to foster collaboration between the scientific community working on Solar System Planets atmospheres and the new growing community of the Ariel Science Team. We show here an overview of on-going studies and future projects foreseen by WG members, mostly focused on using our Solar System planets as proxies to develop and test tools to support Ariel science cases.

CHARACTERIZATION OF JUPITER ATMOSPHERE FROM SPACE AND GROUND BASED OBSERVATIONS

Objective: Jupiter is an archetype for gas giants across the Universe. Its study in detail helps us to determine what is a "typical" gas giant planet like and the processes through which a gas giant works and form (Gapp 2021; Gapp et al. in preparation).
Ariel will play a significant role in observing and analysing gas giants.

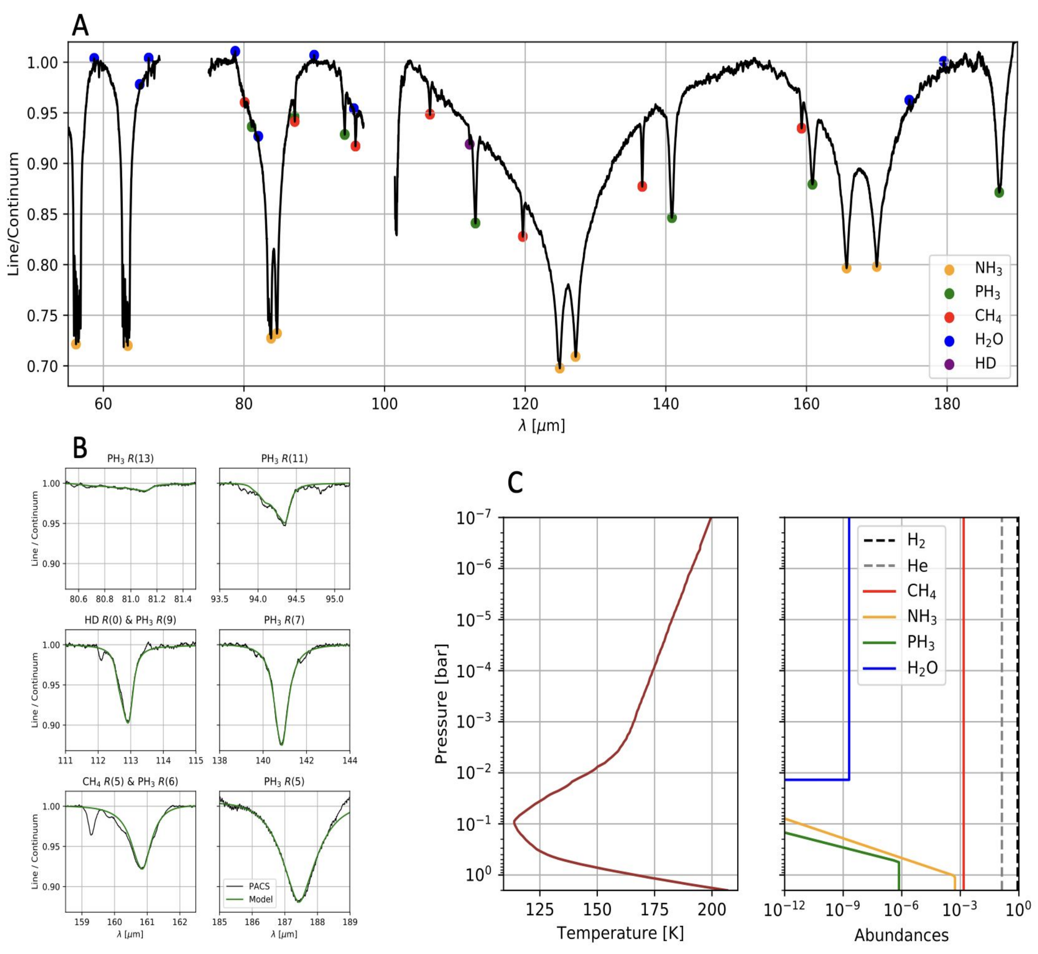

FIGURE 1:

A) The Herschel/PACS spectrum of Jupiter, expressed in line-to-continuum ratios. The coloured dots show the identified spectral features.
B) Observed and best-fit simulated phosphine bands (black and green, respectively).
C) Left: The adopted temperature profile (Nixon et al. 2007, Fletcher et al. 2009) Right: the chemical composition of the Jovian atmosphere inferred from the PACS observations

THE SOLAR SYSTEM AS SEEN FROM OUTSIDE

Question: If we were observing the Solar system from a remote point in the ecliptic plane, what would we see, and what would we learn?

Answers:

- The Solar system would NOT be seen as a multiple system (apart from a few exceptional positions) because, compared to exoplanetary systems, the planets are far from the Sun and the inclinations of their orbits are not negligible;
- The contribution of the planets to the Solar system light curve would be very small; the contribution of Jupiter and Venus would be dominant in the visible, while the contribution of Mercury would prevail at 10 μm;
- Transit spectra of the planets (figures below) would probe the atmospheres above the tropopause only.

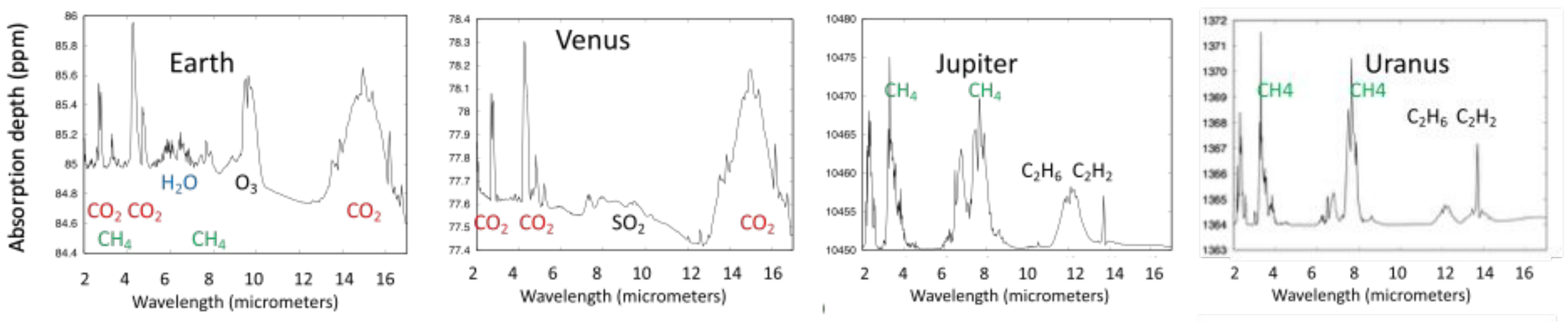

FIGURE 2: Simulated transit spectra of four solar system planets as labeled, calculated with the PSG (Villanueva et al. 2018) with a resolving power of 200.
(Figures extracted from Encrenaz et al. 2022)

3D SIMULATIONS OF VENUS-LIKE PLANETS

Objective: Study simulations and phase curves from 3D model outputs to investigate variability (if observed) and which physical information about the planet's atmosphere we can infer from Ariel phase curves of rocky planets
Method: Generic Planet Climate model (Generic-PCM) (e.g. Turbet et al. 2016, Forget & Leconte 2013) applied to specific cases of known rocky planets (e.g., Trappist-1c, LP 890-9c) under the hypothesis that their atmospheres evolved into a modern Venus (Quirino et al. 2023).

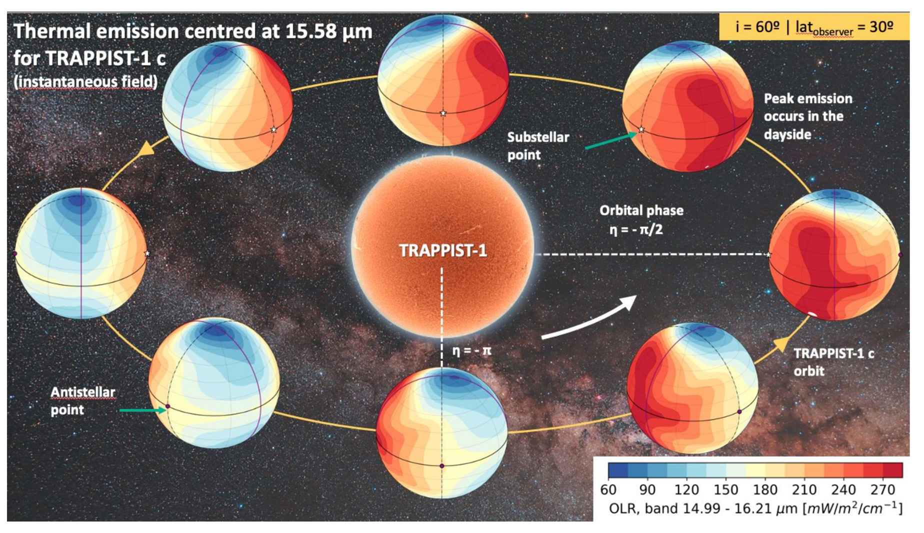

FIGURE 3: Example of Outgoing Longwave Radiation (OLR) around 15-μm simulated with the Generic-PCM and used as input to compute thermal phase curves (credit: Quirino D. (2022) Master's Thesis)

Results: The largest amplitude modulation (~13 ppm) occurs between the transit and the secondary eclipse at around 15-μm, making this detection potentially feasible with JWST, but not with ARIEL.

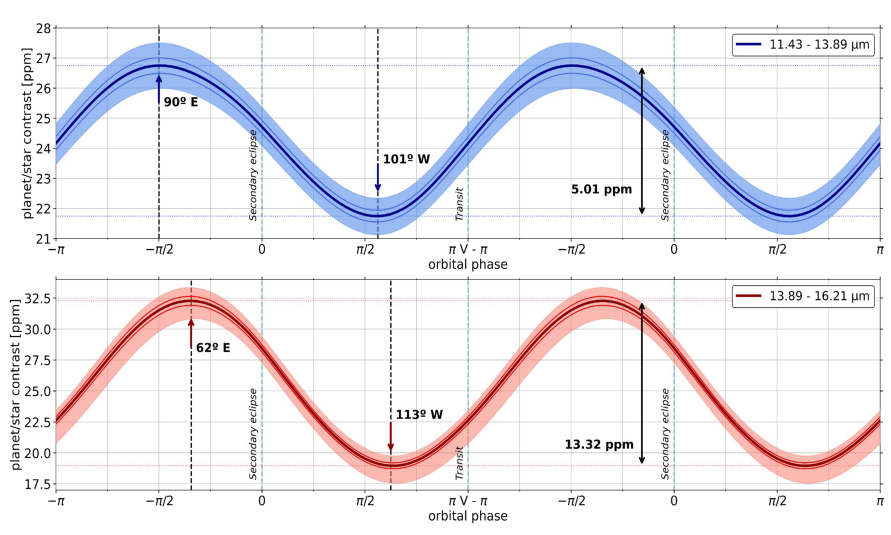

FIGURE 4: Example of thermal phase curves time-averaged over ten orbits of TRAPPIST-1c for two bands: *continuum* (upper panel) and 15-μm CO_2 absorption band (lower panel).

OBSERVABILITY OF TEMPERATE EXOPLANETS WITH ARIEL

Objective: identify "temperate" exoplanets (T = 350-550 K) to be observable in the Tier 2 spectroscopic mode of Ariel for constraining their atmospheric composition

Method: start from the Edwards & Tinetti (2022) list and select the observable targets using ArielRad (Mugnai et al. 2020)

The candidates: Gaseous giants / Big & small Neptunes ($M > 5\ M_E$)

#	Candidate	Stellar mass (MS)	Mass (ME)	Radius (RE) T	Teq (K)	Period (days)	T2
1	TOI-1227 b	0.17	57.6	8.7	512	60	13
2	Au MIC c	0.5	22.2	3.2	479	18	13
3	TOI-3884 b	0.28	16.5	6.0	474	4.5	1
4	TOI-1231 b	0.49	15.4	3.6	339	24.2	12
5	TOI-1759 b	0.61	10.8	3.1	456	19	22
6 (excluded)	TOI-2076 d	0.82	10.5	3.2	511	35	20
7	LTT-3780 c	0.40	6.3	2.3	363	5.3	25
8	LP-791-18 c	0.14	6.0	2.3	351	5.0	22

5, 7 and 8 are considered as sub-Neptunes in the literature
(Martioli et al. 2022, Nowak et al. 2020, Cloutier et al. 2020, Crossfield et al. 2019)

Results: 7 gaseous exoplanets ($M > 5\ M_E$) + 8 super-Earths/small Neptunes ($1.5\ M_E < M < 5\ M_E$) are identified as observable targets in the Tier 2 mode

The candidates: Super-Earths/Small Neptunes ($1.5\ M_E$-$5\ M_E$)

#	Candidate	Stellar mass (MS)	Mass (ME)	Radius (RE) T	Teq (K)	Period (days)	T2
9	TOI-270 d	0.39	4.8	2.1	398	11.3	15
10	TOI-776 b	0.54	4.0	1.8	530	8.2	32
11	TOI-178 g	0.65	3.9	2.9	483	20.7	19
12	LTT 1445 A b	0.26	2.9	1.3	440	12.2	8
13	L 98-59 c	0.27	2.2	1.4	534	3.7	7
14	L 98-59 d	0.27	1.9	1.5	422	7.4	6
15	LHS 1140 c	0.19	1.7	1.2	411	3.8	28
16	LTT 1445 A c	0.26	1.5	1.1	527	3.1	9

Observations of these targets in Tier 2 will allow us to discriminate between small Neptunes and super-Earth

SOME FUTURE WORKS

- Take into account recent efforts carried out with JWST observations, and future efforts with JUICE to use Jupiter as benchmark for gas giant planets.
- Study Uranus and Neptune, more representative of colder objects, as proxies of a subcategory of ice giants planets
- Use GCMs and convection-resolving models to study the terrestrial exoplanets cloud characteristics (spatial coverage, altitude range, temporal variability) for different surface pressure and atmospheric dynamical regime to help analysing the data through the observation of phase curves of exoplanets.
- We plan to analyse the transmission spectrum of the atmosphere of Venus obtained with high resolution observations performed with FIRS instrument at Dunn telescope during the solar transit in June 2012 (the last one before 2117), to produce a valuable template of a transit of Venus-like planets around Sun-like stars in a unique calibration opportunity.
- Use Earth resolved spectra to craft observations of Earth-like planets with different percentages of surface/cloud endmembers in the field of view. By integrating these observations into a single pixel, it is possible to derive the percentages needed to identify each endmember in the resulting spectrum. Even if not directly related to the science that Ariel will be doing, such an analysis can provide a good framework to understand what we expect to see in these objects.

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