Using high resolution cross correlation spectroscopy to probe oxygen fugacity regimes in lava ocean worlds

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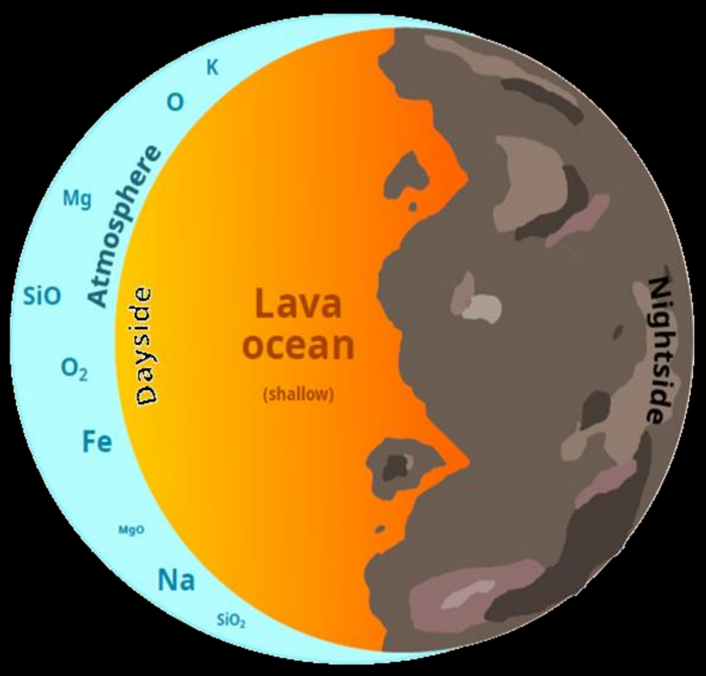
SCAN ME

1. INTRODUCTION

Lava Ocean Worlds - Characteristics



Credits: Fabian Seidler

Very hot highly irradiated exoplanets close to their host stars and tidally locked.

Either newly formed exoplanets, or exoplanets with their primary atmospheres stripped off.

Dayside facing mantle surface is melted to a shallow level due to high irradiation and is in equilibrium with entirety of secondary atmosphere formed from vapourisation of the surface.

Secondary atmosphere often rich in metal and metallic oxides – high UV & optical absorption – thermal inversions expected

Atmospheric characterization in emission can help characterize surface-atmosphere connection!

Oxygen fugacity and its effect on atmospheric composition

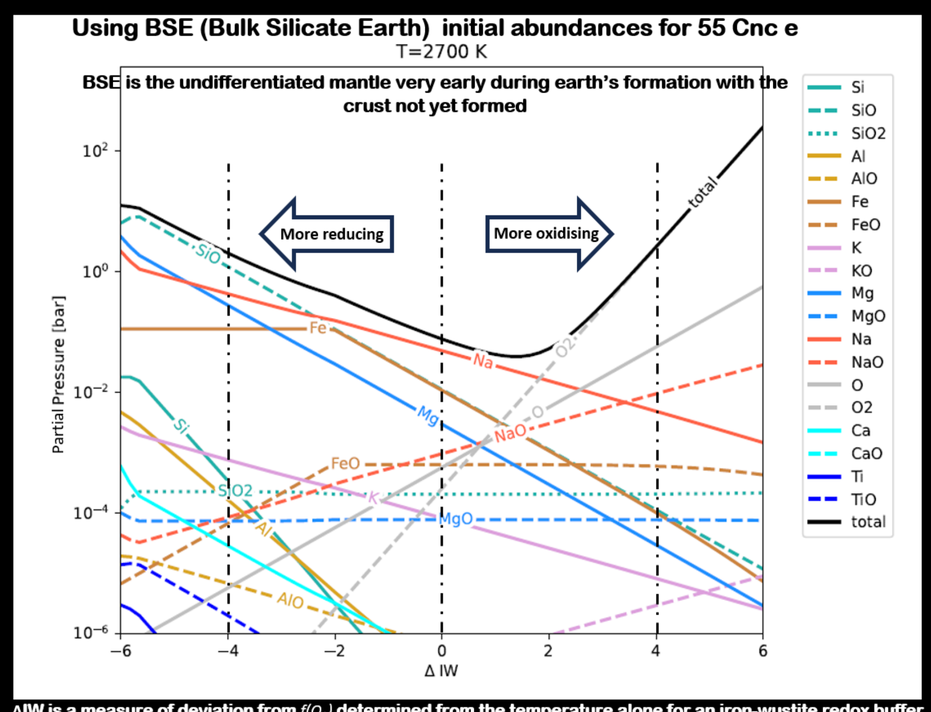
Fugacity – partial pressure equivalent for a 'real' gas

Initial fugacity of oxygen $f(O_2)$ determines the composition of the core as well as the atmosphere that is outgassed from the upper mantle.

Profound influence on the habitability and further fate of the exoplanet

Determining initial oxygen fugacity is difficult as oxygen can act as both a volatile and a refractory element during nebular condensation.

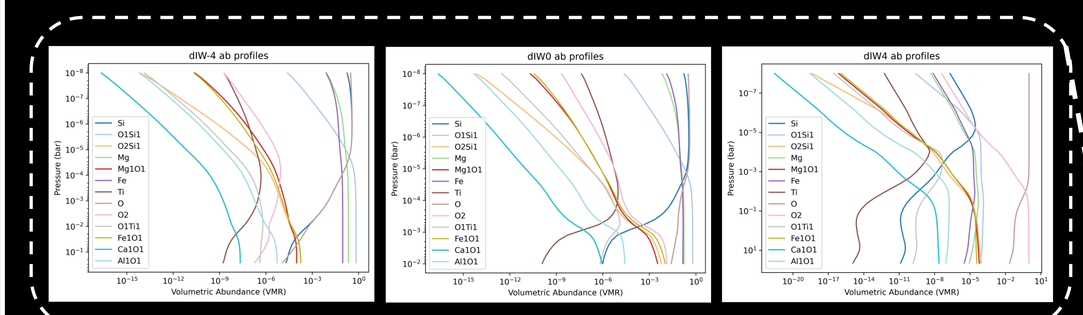
Note: We use 55 Cnc e as a lava ocean world equivalent in our study. However, its status as a lava world is disputed from JWST NIRCam+MIRI data[1].

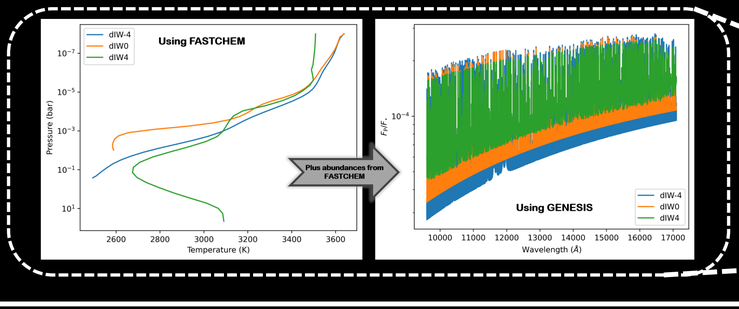


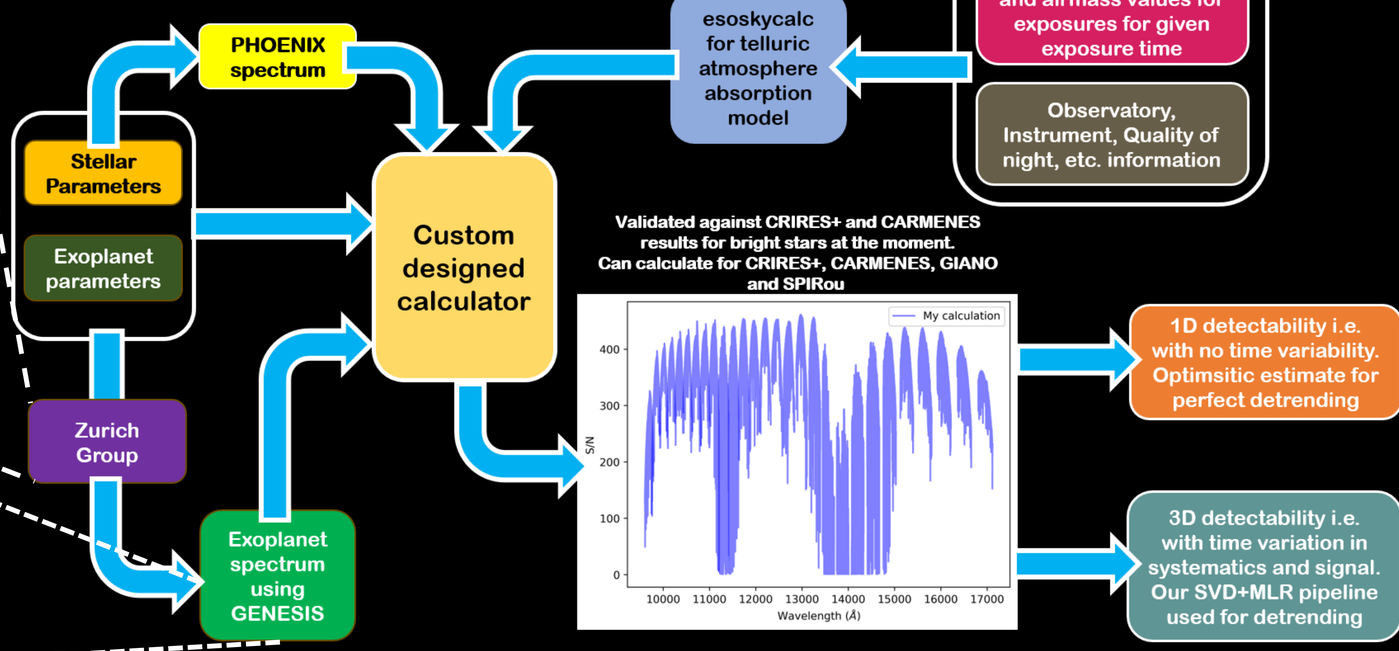
ΔIW is a measure of deviation from $f(O_2)$ determined from the temperature alone for an iron-wustite redox buffer

2. METHODOLOGY

Introducing our end to end S/N calculator for ground based spectrographs!



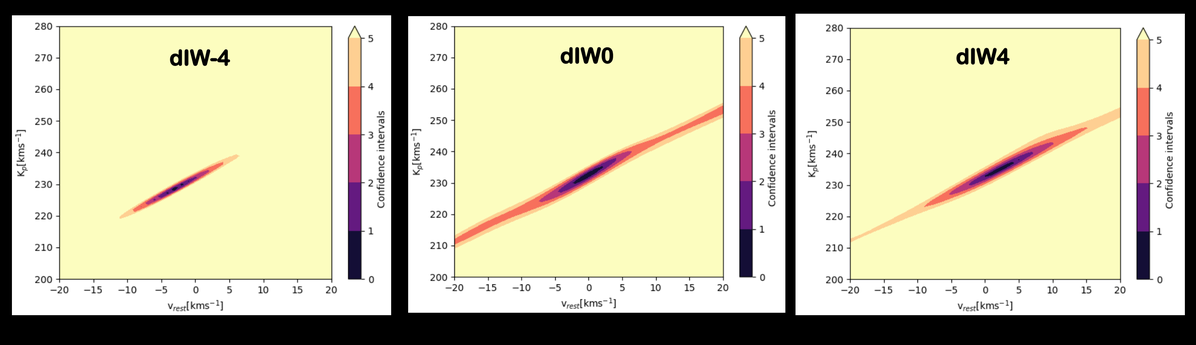




3. RESULTS

1. Results from our SVD/PCA based detrending and reprocessing pipeline [2]

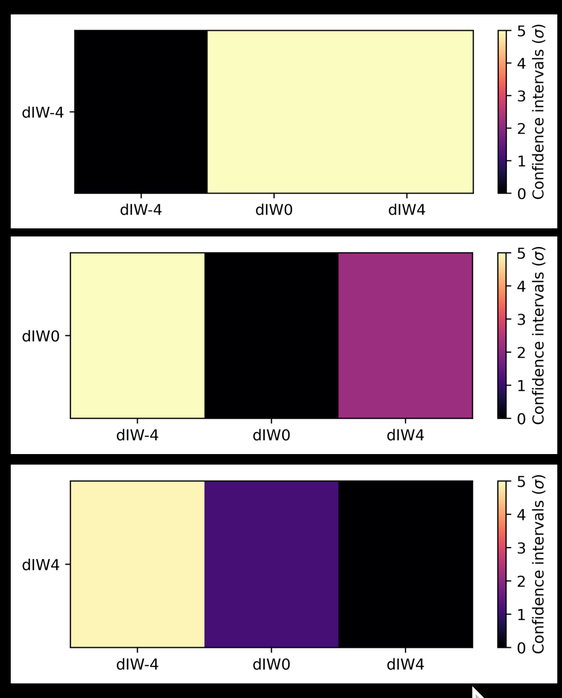
Simulated night is a 5-hour slot using CARMENES from 21:30-02:30 UTC on March 7, 2024, with 300s exposures leading to 53 exposures in total. It covers a phase range of ~0.65-0.95. Airmass never goes beyond 2 and ppv is chosen between 2.5 and 3.5 mm.



All three models can be detected using this one simulated night, but the level of detection varies.

Can these models however be differentiated from each other?

2. Model selection on a grid



dIW-4 case selects for dIW-4 model strongly in favour of other models as expected.

dIW0 case selects for dIW0 model but is only able to reject dIW4 model at ~2-3σ. Still rejects dIW-4 model strongly. Hence, it is overall tricky to differentiate between the 0 and 4 cases.

dIW4 case selects for dIW4 model but is only able to reject dIW0 model at ~1-2σ. Still rejects dIW-4 model strongly. The earlier conclusion of it being difficult to differentiate between 0 and 4 cases is again reiterated.

TAKE HOME MESSAGE

1. Fugacity of oxygen inherited during formation is an indicator of secondary atmospheric composition for lava ocean worlds.

2. This imposed fugacity of oxygen during formation can result in three general classes of exoplanetary atmospheres. All of them showcase thermal inversions and produce observable differences in their emission spectra at high resolution.

3. Detecting these spectral classes is already within current instrumental capabilities by using HRCCS, at least for the case of 55 Cnc e (and similar objects), as demonstrated by our custom made end to end SNR pipeline.

4. While the strongly reducing case is already differentiable from the other classes of atmospheres using current instrumentation, differentiating between the non-reduced cases in comparison to an iron-wustite buffer is however challenging and under further investigation.

REFERENCES

[1] Hu, R., Bello-Arufe, A., Zhang, M. *et al.* A secondary atmosphere on the rocky Exoplanet 55 Cancri e. *Nature* (2024). https://doi.org/10.1038/s41586-024-07432-x

[2] Spandan Dash, Matteo Brogi, Siddharth Gandhi, Marina Lafarga, Annabella Meech, Aaron Bello-Arufe, Peter J Wheatley, Constraints on atmospheric water abundance and cloud deck pressure in the warm Neptune GJ 3470 b via CARMENES transmission spectroscopy, *Monthly Notices of the Royal Astronomical Society*, Volume 530, Issue 3, May 2024, Pages 3100–3116, https://doi.org/10.1093/mnras/stae997