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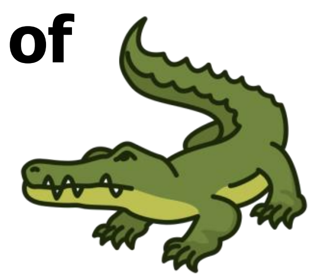
« We integrate cross-correlation spectroscopy of directly-imaged exoplanets into the framework of atmospheric retrievals to measure their molecular abundances and infer their C/O ratio »

CROCODILE CROss-COrrelation retrievals of Directly-Imaged self-Luminous Exoplanets



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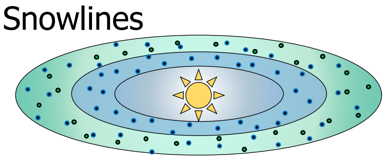
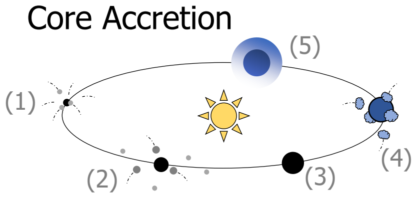
(1) C/O: A CLUE OF PLANET FORMATION

Snowlines



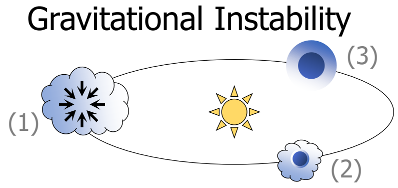
Snowlines indicate the distance from the star where different molecules condensate. They **modify the local elemental abundance** ratios of gases and solids in the disk [1].

Core Accretion



In this scenario, a planetary core first builds up by accretion of solids, after which it starts to accumulate its gaseous envelope. Therefore, its **atmosphere inherits the chemical composition of the gas** in the disk [2].

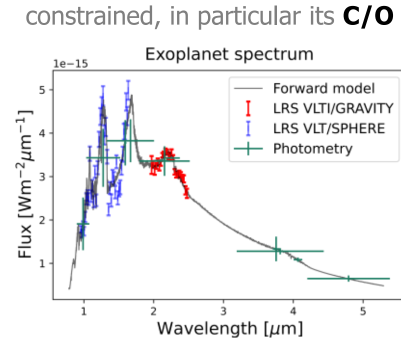
Gravitational Instability

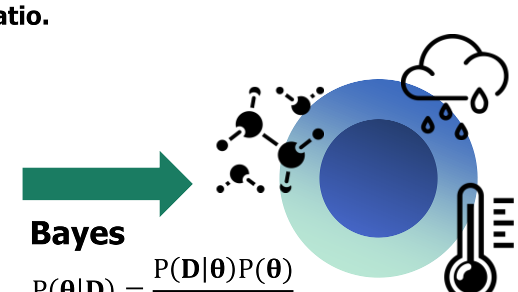


Here, the circumstellar disk fragments into clumps that collapse under self-gravity before contracting and cooling down. The planetary **atmosphere is therefore enriched by solids from the disk** [2].

(2) ATMOSPHERIC RETRIEVALS

CROCODILE is an atmospheric retrieval routine that can be used to **interpret the spectra of directly-imaged exoplanets**. It works by fitting a forward model calculated with *petitRADTRANS* [3] of the planetary atmosphere to photometric and spectroscopic data using Monte-Carlo methods and Bayes theorem.
From the resulting posterior distributions, the **thermal structure, cloud** characteristics, and **chemical composition** of the planetary atmosphere can be constrained, in particular its **C/O ratio.**

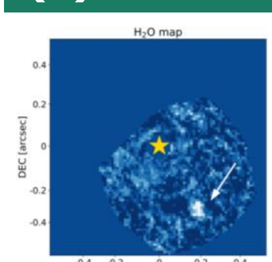




Bayes

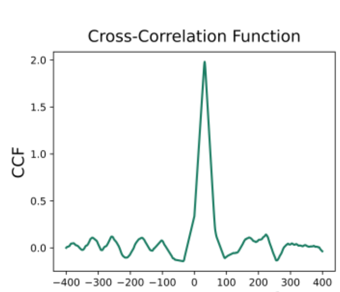
$$P(\boldsymbol{\theta}|\mathbf{D}) = \frac{P(\mathbf{D}|\boldsymbol{\theta})P(\boldsymbol{\theta})}{P(\mathbf{D})}$$

(3) CROSS-CORRELATION SPECTROSCOPY



Taking spectroscopic measurements of directly-imaged exoplanets is challenging because the stellar PSF dominates the field-of-view. However, we can **isolate the signal of the planet by cross-correlating the spectrum** at every spatial coordinate **with molecular templates**, thereby filtering out the stellar light (left figure [4]).

By switching spectral templates, the cross-correlation function (right figure) can be used to **detect individual molecular species.**



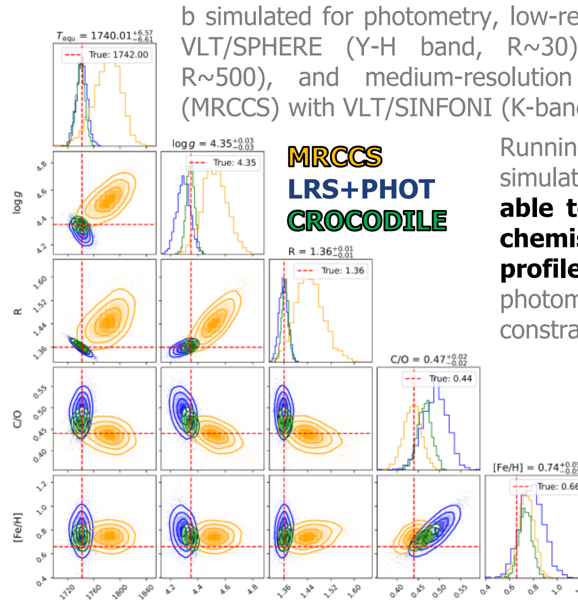
We adapt this technique to atmospheric retrievals by expanding the Gaussian likelihood function to include the cross-correlation R between model and data, following [5]:

$$\log P(\boldsymbol{D}|\boldsymbol{\theta}) = -\frac{1}{2}\sum\left(\frac{D_i - M_i}{\sigma_i}\right)^2 = -\frac{N}{2}\log({s_D}^2 + {s_M}^2 - 2R)$$

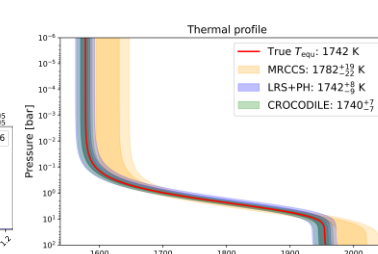
CROCODILE is able to combine cross-correlation spectroscopy together with photometry and regular spectroscopy by adding their respective log-likelihood functions.

(4) RESULTS

We validate our framework on a simple synthetic model of β Pic b simulated for photometry, low-resolution spectroscopy (LRS) with VLT/SPHERE (Y-H band, R~30) and VLTI/GRAVITY (K-band, R~500), and medium-resolution cross-correlation spectroscopy (MRCCS) with VLT/SINFONI (K-band, R~4000).



Running CROCODILE on subsets of the simulated data, we find that **MRCCS is able to constrain the atmospheric chemistry better than the p-T profile.** Combining it with LRS and photometry provides less biased constraints.



(5) CONCLUSION

Extending our test to synthetic targets with different temperature, C/O ratio, and metallicity, we find that CROCODILE can obtain more robust constraints of the atmospheric parameters, in particular the C/O ratio, when combining MRCCS with LRS and photometry.

References
[1] Öberg, K. I., Murray-Clay, R., & Bergin, E. A. 2011, ApJ, 743, L16
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[4] Cugno, G., Patapis, P., Stolker, T., et al. 2021, A&A, 653, A12
[5] Brogi, M. & Line, M. R. 2019, AJ, 157, 114

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