New applications for planet atmosphere characterisation - Lessons learned from binaries -

D. Sebastian[1], A. H.M.J. Triaud[1], M. Brogi[2,3,4]
& the EBLM team

[1]School of Physics & Astronomy, University of Birmingham, Edgbaston, Birmimgham, B15 2TT, UK
[2]Dipartimento di Fisica, Università degli Studi di Torino, via Pietro Giuria 1, I-10125 Torino, Italy
[3]Department of Physics, University of Warwick, Coventry CV4 7AL, UK
[4]INAF-Osservatorio Astrofisico di Torino, Via Osservatorio 20, I-10025 Pino Torinese, Italy

Funded by the European Union

European Research Council
Established by the European Commission

Why do we do this?

High-resolution cross-correlation techniques are commonly used to detect atomic or molecular species in the atmospheres of hot and ultra-hot Exoplanets. By analysing transit observations, as well as reflected light, these species can be traced over several parts of the planetary orbit. Using high signal-to-noise observations with future large aperture instruments will allow us to test models of exoplanet atmospheres including winds as well as the spatial distribution of molecules.

With this goal, we develop **`Saltire`**, a tool to model the 2D shape of the Cross-correlation signal of such observations. The model performs a 2D fit to the signal, allowing to measure its position accurately.

We apply these correlation techniques for the first time to a **high-contrast binary** showing, that the `Saltire` model facilitates precise dynamical mass measurements. By applying Saltire to infrared observations of the giant planet **τ Boötis b**, we show its versatility to precisely measure molecular signals from exoplanet atmospheres. We also show how `Saltire` can be used to model phase-dependent atmospheric signals.

Modelling exoplanet CCF signals
Sebastian et al. 2023B, subm.

Exoplanet atmospheres are routinely analysed in the K_c-V_{sys} plane.

The 2D CCF shape is defined by the **K-focusing** process: Where the signal amplification happens by combining all observed spectra in the planet's rest-frame.

It depends on:

- The **1D CCF shape and contrast** ratio at each point of observation
- The Reflex motion of the exoplanet (with unknown semi-amplitude K_c)
- The **orbital phase** of each observation

`Saltire` models the 2D shape in the K_c-V_{sys} plane by:

- Using a 1D CCF function to account for the signal as well as the side-lobes
- modeling the **K-focusing** process, based on the exact observational cadence.

Saltire in action!

- We model the CO detection in τ Boötis b using CRIRES data from Brogi et al. 2012
- Full 2D CCF shape of CO detection is recovered
- Measure 2D CO signal position
  - 10x more accurate, compared to 1D Gaussian fit

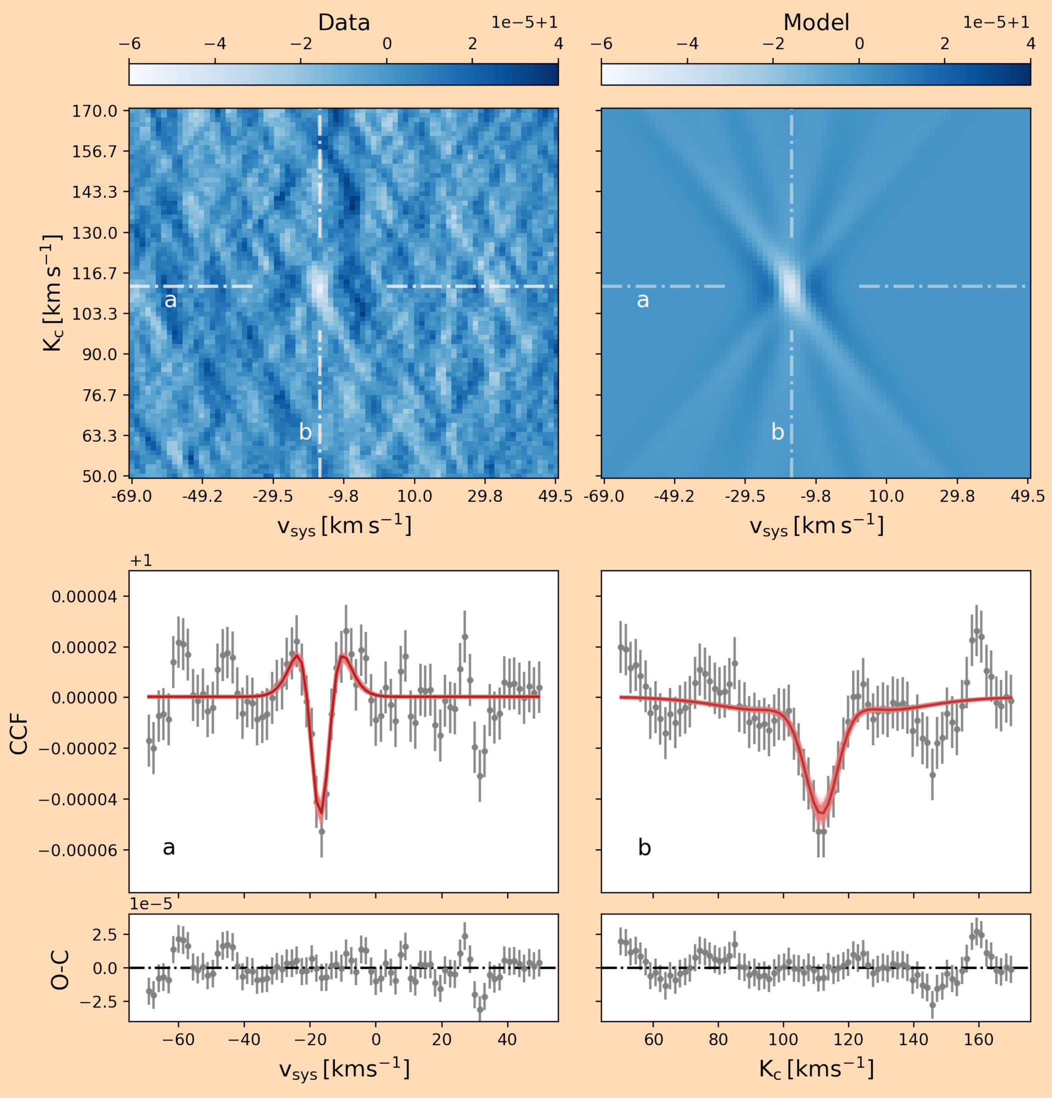
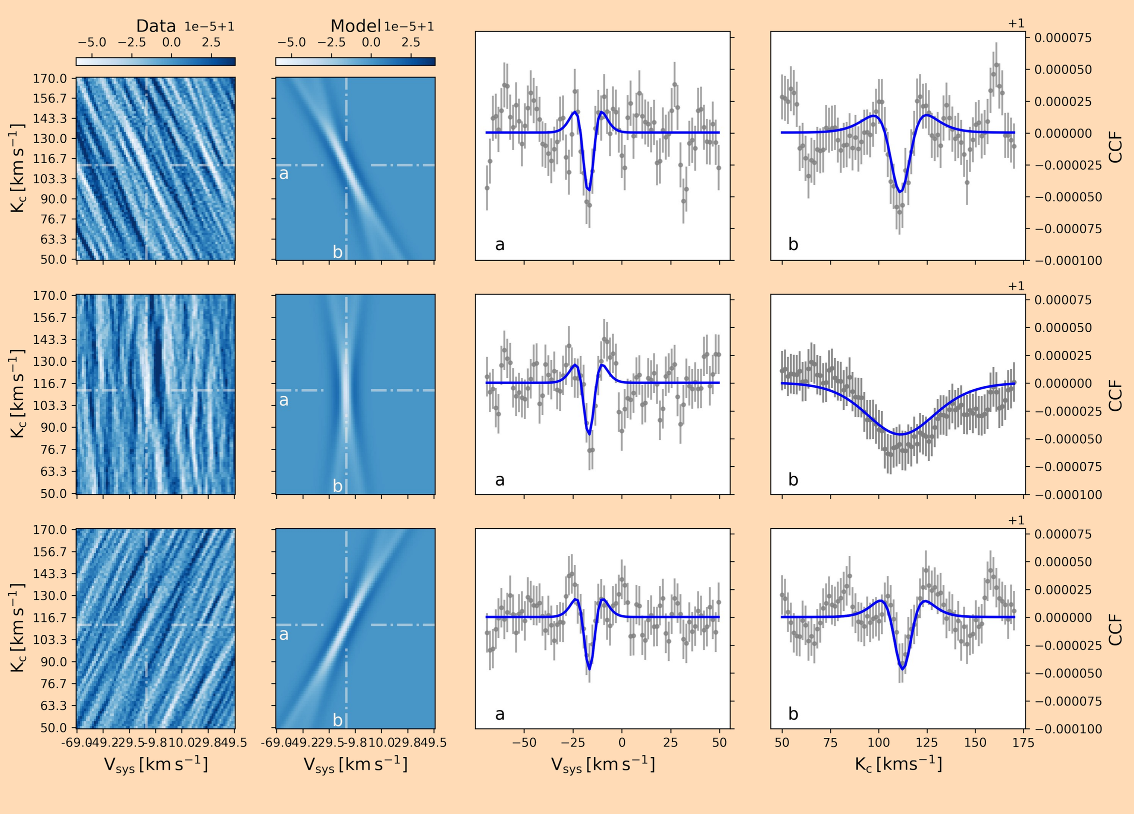


Fig1
Left: The CCF map of τ Boötis b.
Right: Saltire model map of the same observation
Lower panels: Comparison of data and best fitting model

Predicting the shape of the signal



`Saltire` allows us to:

- Predict phase-dependent CCF shape from observing strategy
- Improve position measure for **transit/eclipse observations**

CRIRES data cover 3 nights at planet's inferior conjunction.

Fig2
Left: The CCF maps of τ Boötis b for single nights. Right: Saltire model evaluated (not fitted) for each night.

Detecting a high-contrast binary component
Sebastian et al 2023c, in press.

Two planets have been discovered, orbiting the high-contrast binary TOI-1338/BEBOP-1.

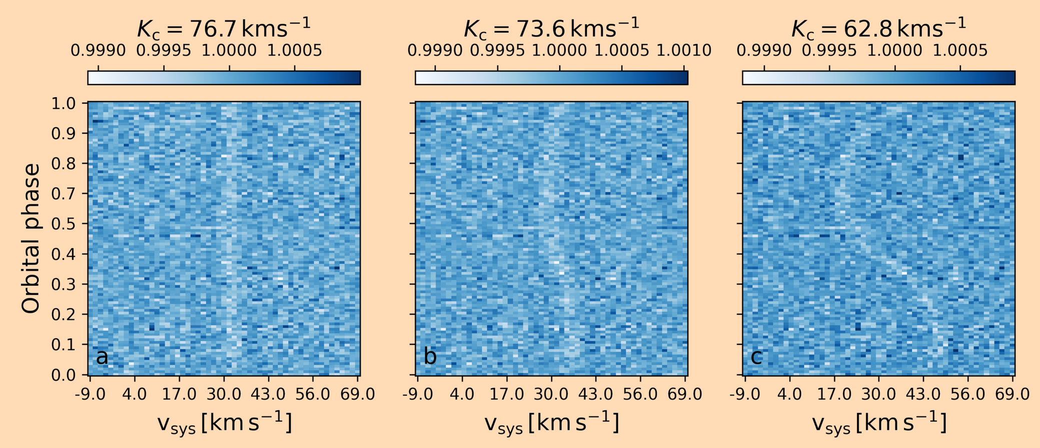
- Planet b the first circumbinary planet from TESS (Kostov et al. 2020),
- Planet c, the first circumbinary planet solely discovered from radial velocities (Standing et al. 2023).

The **binary contrast-ratio of 2e-03**, allows to measure the G-type primary component as a single lined binary (SB1) from ESPRESSO / HARPS spectra.

We apply cross-correlation techniques - from exoplanet atmosphere analyses:

- Removal of the primary spectrum, using singular value decomposition (SVD),
- Cross-correlation of the residuals with a line list, optimised for M-dwarfs,
- Measurement of the CCF signal in the K_c-V_{sys} plane using the **`Saltire`** model.

- **First time, application to a high-contrast binary.**
- **K-focus shape clearly visible**
- **Dynamical (model independent) masses of TOI-1338/BEBOP-1**
- **Mass accuracy:**
  - **2% for the primary**
  - **1% for the secondary**



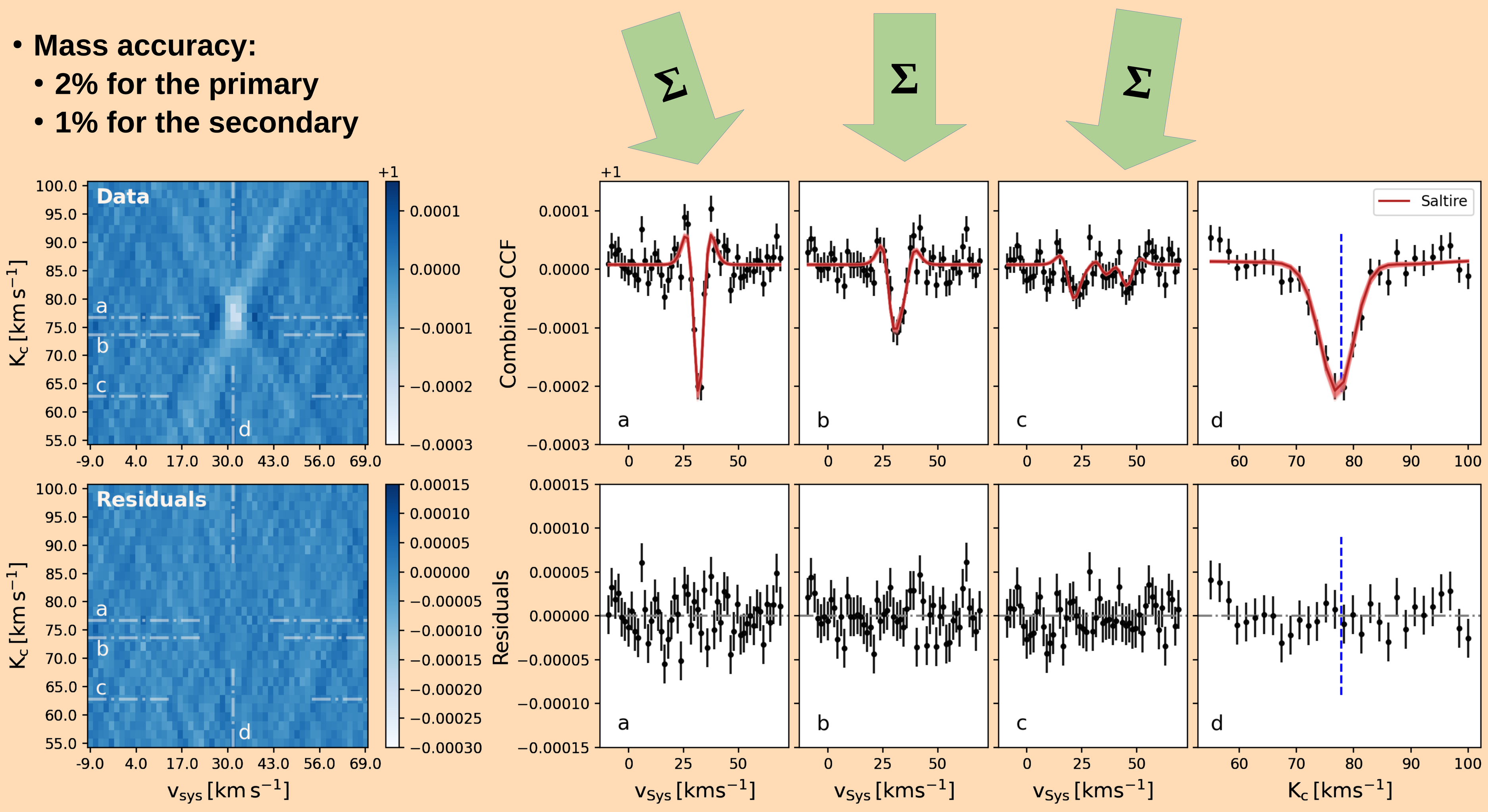


Fig3
The process to derive a CCF map in the K_c-V_{sys} plane (**K- focusing**).
Secondary's CCFs align at best matching orbit (best K_c)
`Saltire` model takes K-focusing process into account.

Detecting a spectroscopic phase curve

- The high detection significance allows us to measure phase dependent CCF contrast.
- CCF contrast is a measure of the binary's contrast ratio.
- We can derive the **spectroscopic phase curve of TOI-1338/BEBOP-1**

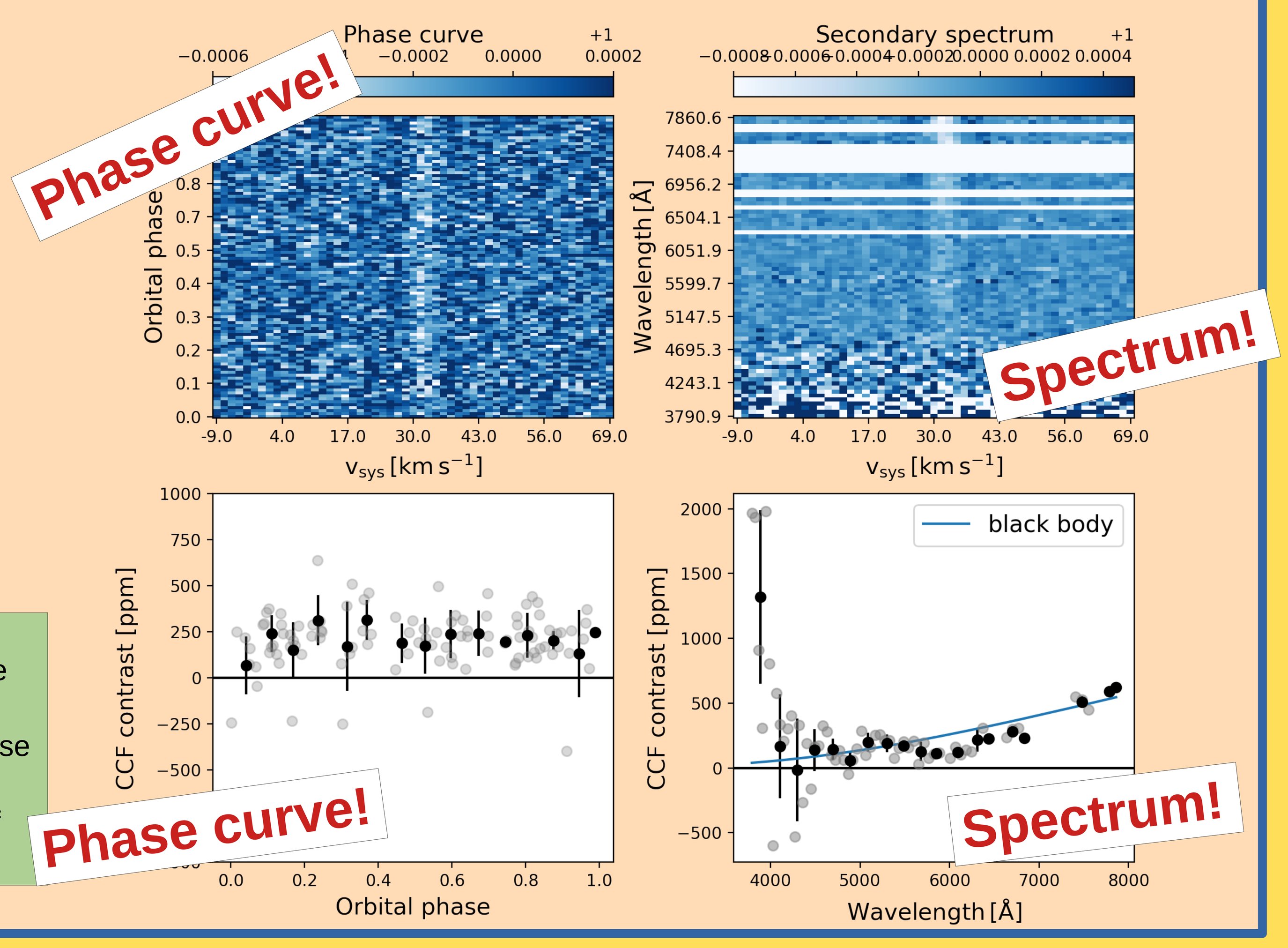


Fig4
The CCF signal is clearly recovered in the Secondary's rest frame. *Left:* phase dependent CCF signal showing a flat phase curve, *Right:* wavelength dependent CCF signal matching the black body spectra of both stars.

The `Saltire` model is easy to use.

Got your own CCF map?

Saltirise it!

https://github.com/dsagred/saltire

SCAN ME

References

Sebastian et al. (2023b), 'Saltire - A model to measure dynamical masses for high-contrast binaries and exoplanets with high-resolution spectroscopy', MNRAS submitted
Sebastian et al. (2023c), The EBLM project – XIII. TOI-1338 - Measuring dynamical Masses of EBLM binaries, in press.
Standing, M. R., Sairam, L., Martin, D. V., et al. (2023) "Radial-velocity discovery of a second planet in the TOI-1338/BEBOP-1 circumbinary system," NatAs, 7, 702-714 – 2023NatAs...7..702S
Brogi, M., Snellen, I. A. G., de Kok, R. J., et al. (2012) "The signature of orbital motion from the dayside of the planet τ Boötis b," Natur, 486, 502-504 - 2012Natur.486..502B
Kostov, V. B., Orosz, J. A., Feinstein, A. D., et al. (2020) "TOI-1338: TESS' First Transiting Circumbinary Planet," AJ, 159, 253 - 2020AJ....159..253K

Contact: D.Sebastian.1@bham.ac.uk