The LHS 1140 System Revisited with the Line-by-line Framework

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Context: The LHS 1140 System

- Two transiting super-Earths around an M4.5:
  - LHS 1140 b, inside the Habitable zone **[1]**
  - LHS 1140 c, an inner, smaller planet **[2]**
- From **ESPRESSO** and TESS data, **[3]** showed that planet b and c are most likely larger versions of the Earth (rocky)

Host star	LHS 1140 b	LHS 1140 c
T_{eff} = 3160 K	P = 24.7 d	P = 3.77 d
Dist. = 15 pc	R_p = 1.6 $R_\oplus$	R_p = 1.2 $R_\oplus$
H = 9.092	M_p = 6.5 $M_\oplus$	M_p = 1.8 $R_\oplus$
P_{rot} = 131 d	T_{eq} ~ 230 K	T_{eq} ~ 410 K

[3]

The Line-by-line Method

- Apply the Bouchy framework **[4]** on individual spectral lines to measure Doppler shifts
- PRV obtained from the weighted average of all per-line velocities after rejecting high-sigma outliers **[5]**
- The line-by-line (**LBL**) method has led to multiple mass characterizations: TOI-1452 b **[6]**, TOI-1759 b **[7]**, TOI-2136 b **[8]**, TOI-1695 b **[9]**, etc.
- **In this study**, we apply the LBL on publicly available ESPRESSO data of LHS 1140 (data set of **[3]**). Published RVs derived from a CCF show more dispersion than LBL ones (Fig. right). The orbital solutions of the planets are significantly improved (see below).

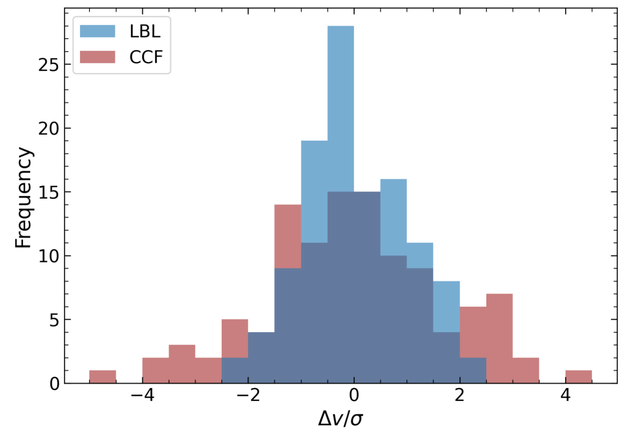
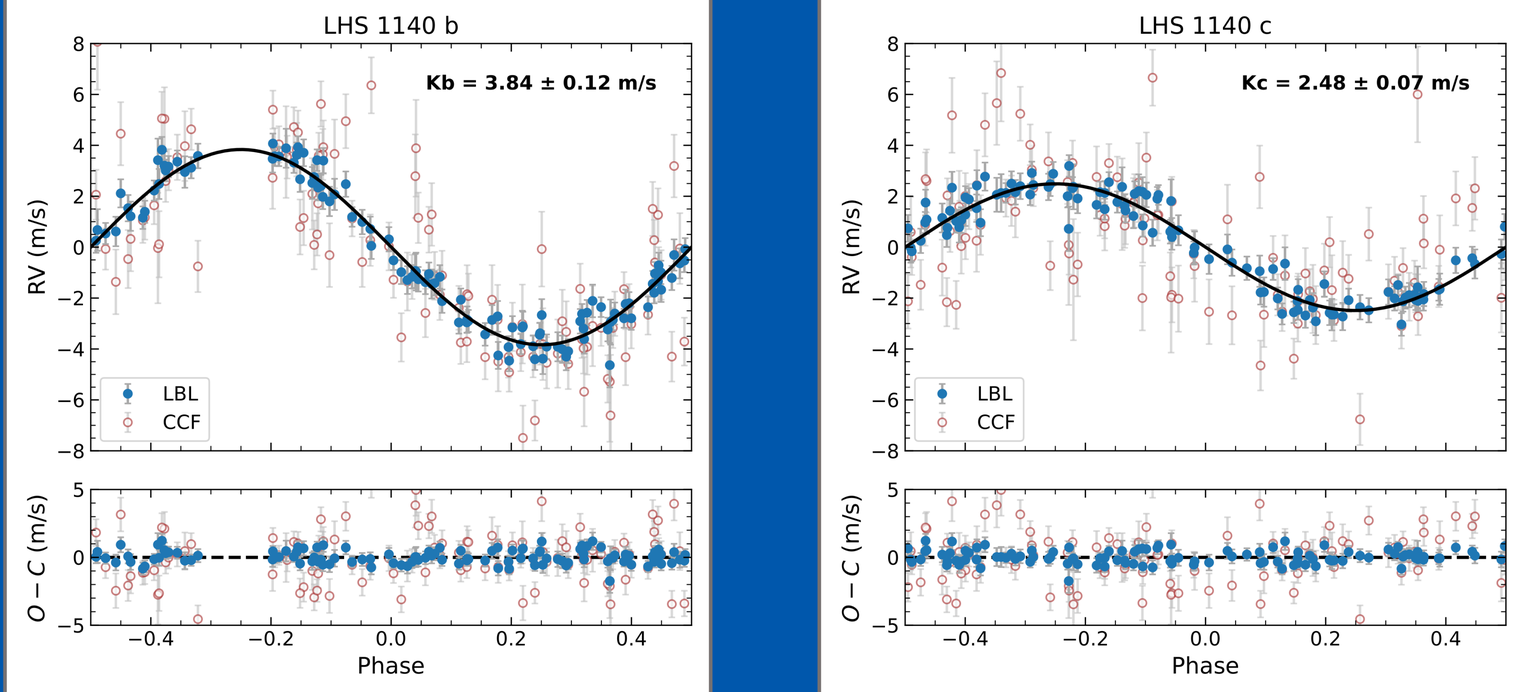


Figure: Normalized RV errors for LBL (blue) and CCF (red) velocities of LHS 1140 observed with ESPRESSO.

ESPRESSO data of LHS 1140 Analyzed with LBL vs. CCF

1. Factor two gain in RV precision: σ_{CCF} = 0.99 m/s, σ_{LBL} = 0.52 m/s

2. Residuals RMS reduced by 70%: RMS_{CCF} = 1.88 m/s, RMS_{LBL} = 0.53 m/s



3. No extra white noise detected: 1.21 m/s for CCF, 0.04 m/s for LBL

4. Mass constraints for LHS 1140 b and c improved by **50%**!

Figure: Phase-folded Keplerian RV signals of LHS 1140 b (left) and LHS 1140 c (right) derived from the line-by-line (blue) and cross-correlation function (red, **[3]**) methods.

Archival Transits

- Our study features 4 *Spitzer* transits (of b), including 3 unpublished ones (PI: Dittmann)
- TESS data from sectors 3 and 30 also included

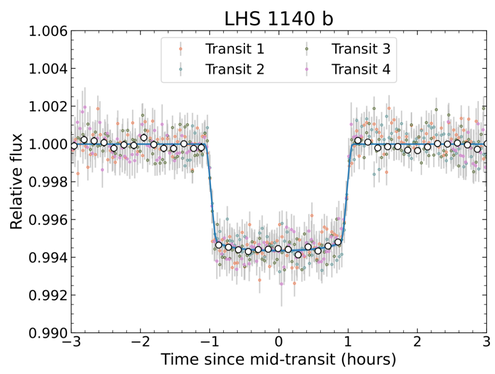


Figure: Stacked transits of LHS 1140 b with *Spitzer*.

A Habitable Zone Water World?

- Our joint analysis of RV and Transit data results in new mass-radius constraints for LHS 1140 b and c
- Notably, LHS 1140 b is now **above** the Earth-like sequence (see Fig.) with a density compatible with a volatile-rich interior (e.g., >1% H_2O by mass)
- The Habitable zone planet LHS 1140 b could be a **snowball** or an **aquaplanet**, i.e., with a frozen or liquid water surface, depending on the level of CO_2 in the atmosphere **[10]**
- Detailed internal structure analysis will be presented in a forthcoming publication (**Cadieux et al. in prep.**)

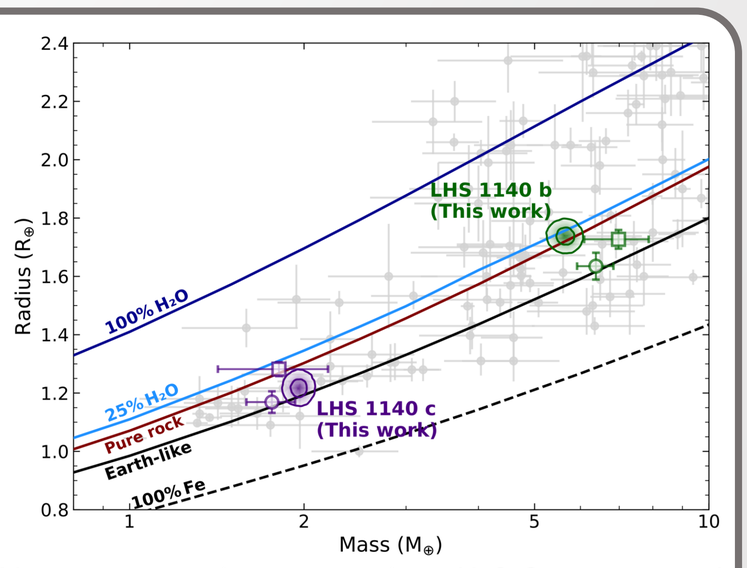


Figure: New mass-radius constraints (1 & 2-σ contours) for LHS 1140 b (green) and c (purple). Previous results of [**2**] and [**3**] are shown with squares and circles.

References:
[1] Dittmann et al. 2017, *Nature*, 544, 333
[2] Ment et al. 2019, AJ, 157, 32
[3] Lillo-box et al. 2020, A&A, 642, A121
[4] Bouchy et al. 2001, A&A, 374, 733
[5] Artigau et al. 2022, AJ, 164, 84
[6] Cadieux et al. 2022, AJ, 164, 96
[7] Martioli et al. 2022, A&A, 660, A86
[8] Gan et al. 2022, MNRAS, 514, 4120
[9] Kiefer et al. 2023, A&A, 670, A136
[10] Marounina & Rogers 2020, ApJ, 890, 107

LBL

The LBL code is publicly available (scan QR code) and compatible with ESPRESSO, HARPS, HARPS-N, SPIRou, NIRPS, and CARMENES-VIS