HIP 41378 b & c: Unveiling the nature of the two sub-Neptunes with transit timing variations using CHEOPS

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Pietro Leonardi[1,2], Luca Borsato[3], Valerio Nascimbeni[3], Giampaolo Piotto[2,4]

[1]Università di Trento; [2]Università degli Studi di Padova [3]INAF -- Osservatorio Astronomico di Padova; [4]Centro di Ateneo di Studi e Attività Spaziali "Giuseppe Colombo" (CISAS)

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Outline: We performed a detailed photometric and dynamical study on HIP 41378 b & c based on 17 new CHEOPS visits (GTO ID CH_PR100025), seven TESS sectors, as well as previously published data from K2, Spitzer, HST and HARPS to reassess the characteristics of the system and precisely measured the radii and masses of the planets.

Introduction

- As of now we have discovered more than **5500 planets** orbiting other stars.
- As an exoplanet passes in front of its host star (in our line of sight) the light we receive from the star will decrease in brightness (see Fig. 1). By observing this dip in brightness during a planetary transit we can determine various planetary parameters.
- Precise knowledge of a planet **mass and radius** is essential to infer its **internal structure and the presence of an atmosphere.** This is especially important for small planet ($R < 4\ R_\oplus$), a wide range of compositions are possible for these planets, whose mass and size lie between those of the Earth and Neptune (i.e. Super-Earths and Sub-Neptunes)

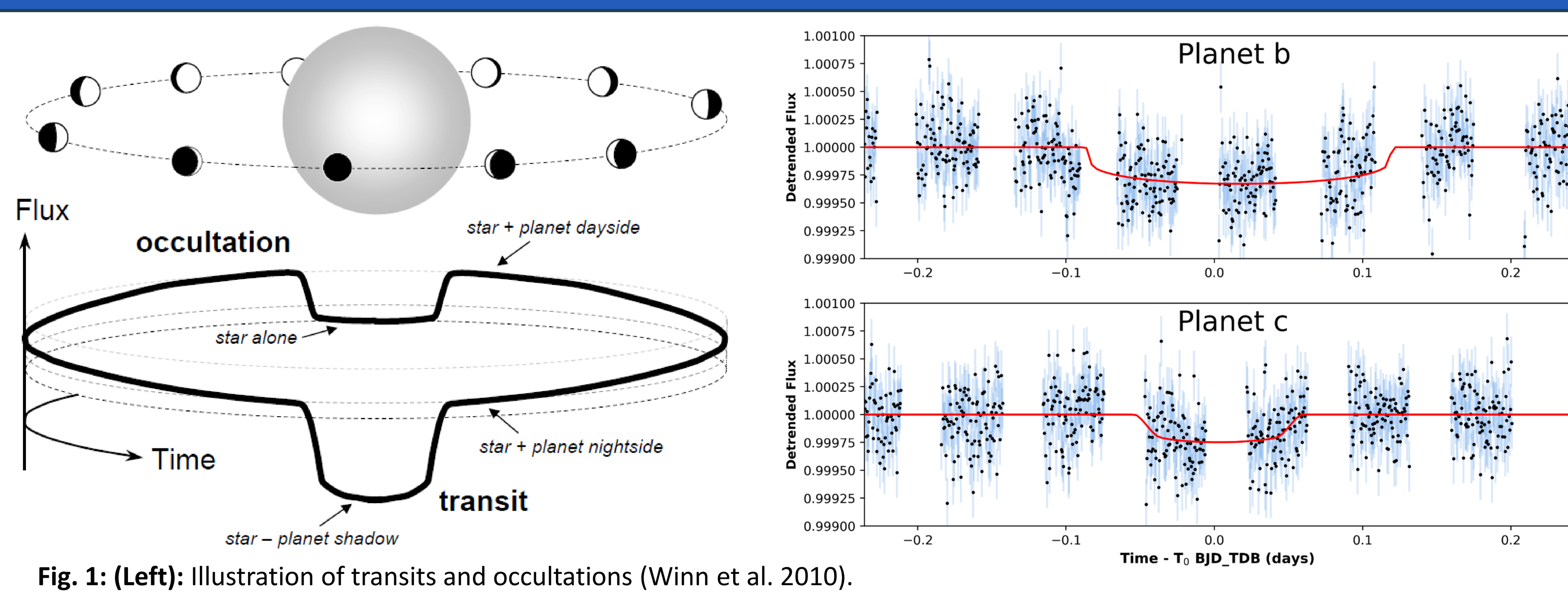


Fig. 1: (Left): Illustration of transits and occultations (Winn et al. 2010).
(Right): CHEOPS observation of HIP 41378 b & c folded on the best-fit individual T0. The best-fit transit model is overplotted on top (red).

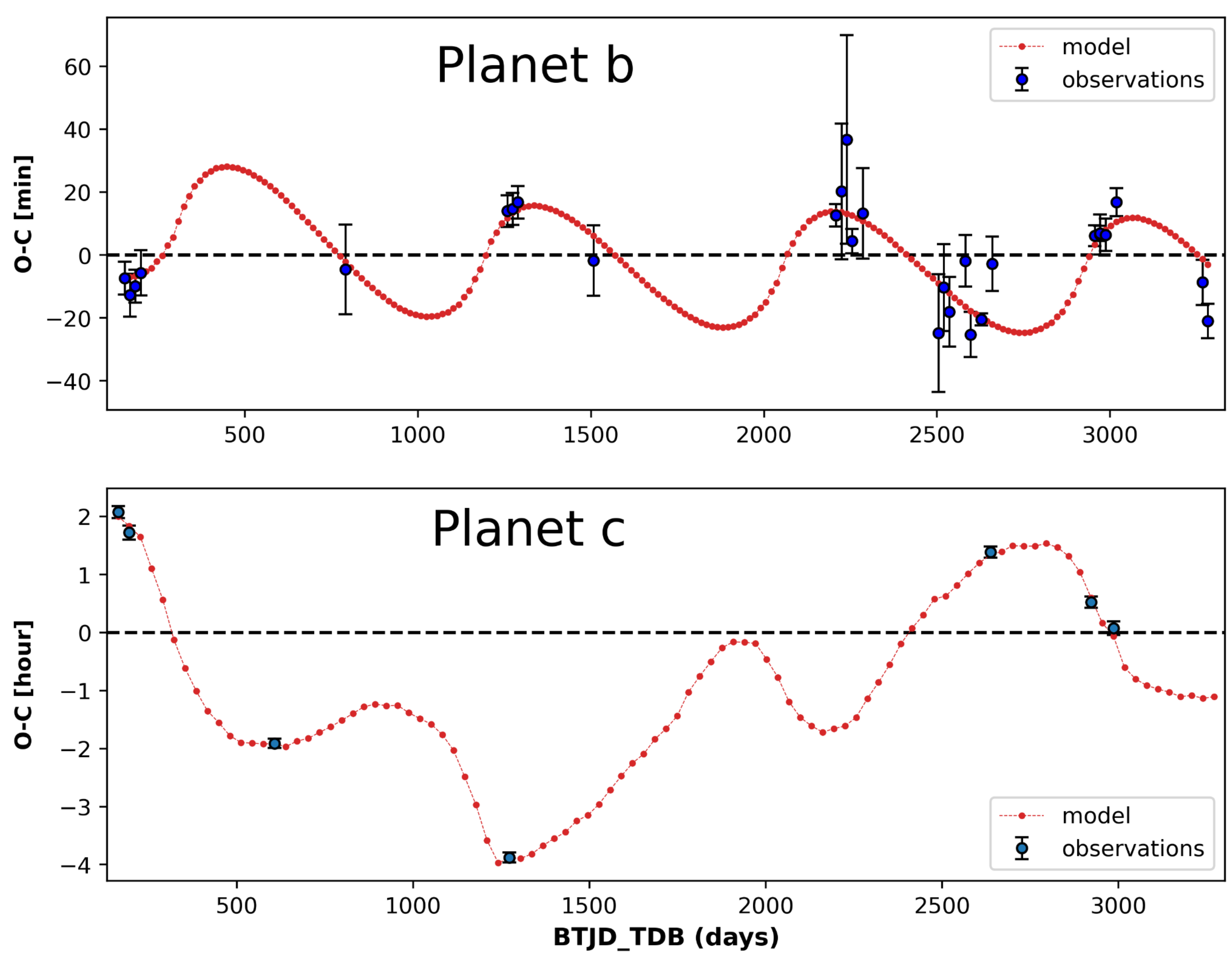


Fig.2: Observed minus Calculated (O − C) diagram of HIP 41378 b (top) and HIP 41378 c (bottom) from the dynamical integration with TRADES. The vertical axis represents the deviation from the best fitting linear ephemeris and the horizontal axis the Barycentric Julian Date (BJD) of the observations.

Transit Timing Variations

The **transit timing method (TTV)** is an indirect technique used to study exoplanets. It focuses on measuring the precise timing of the transits. When multiple exoplanets are present in a system, their **gravitational interactions** can cause slight variations in the timing of their transits respect to the linear ephemeris which assumes a constant period (see Fig. 2). By carefully **analyzing these timing deviations**, we can infer the presence and properties of **additional exoplanets in the system,** including ones that may be too small to detect using other methods.

Data analysis and dynamical Modeling

- We homogeneously analyzed the photometric data to retrieve the individual central transit times T0 of the photometric datasets (i.e. CHEOPS, TESS, K2, HST and Spitzer) with PyORBIT (Malavolta et al. 2016, 2018)
- We employed the TRADES dynamical integrator (Borsato et al. 2014, 2019, 2021) to fit the transit times (T0) and RVs simultaneously.

Results

Derived parameters for the planets :

- **HIP 41378 b**: $R_b = 2.51 \pm 0.024\ R_\oplus$, $M_b = 7.04 \pm 0.59\ M_\oplus$
- **HIP 41378 c**: $R_c = 2.63 \pm 0.091\ R_\oplus$, $M_c = 2.18 \pm 0.21\ M_\oplus$
- **HIP 41378 g**: $M_g = 3.37 \pm 0.086\ M_\oplus$, $P_g = 56.319 \pm 0.0064$ days

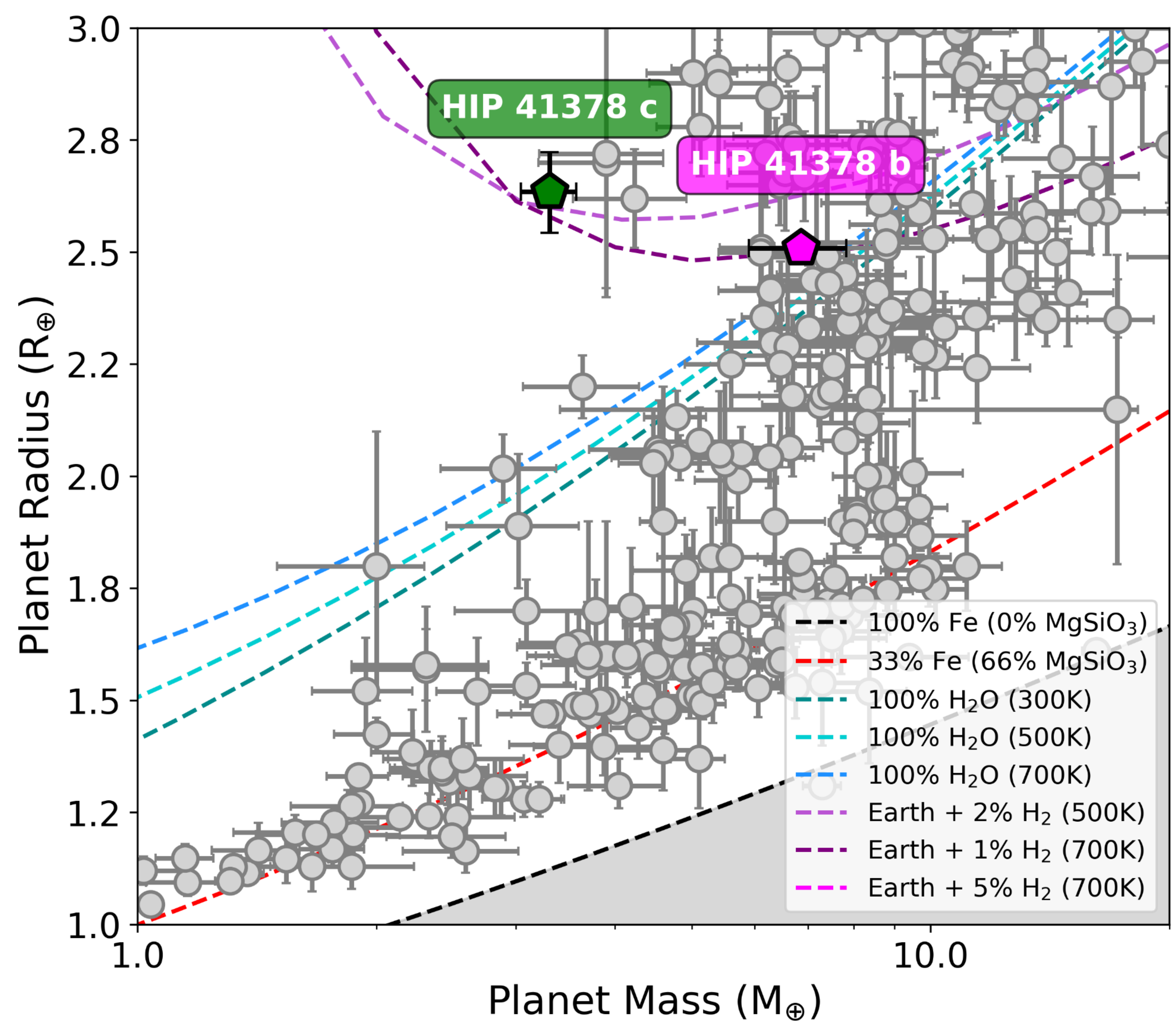


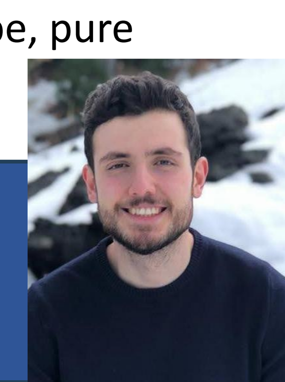
Fig. 4: Mass-radius diagram (Castro-González et al. 2023)— measurements are taken from the NASA Exoplanet Archive with mass and radius precision lower than 20%. Planetary models from Zeng et al. 2019 are plotted as color-coded lines. (Models: Earth-like core with 1%, 2% and 5% of the planet's mass in a H_2/He envelope, pure Iron (100% Fe), Earth-like Rocky (32.5% Fe+67.5% MgSiO3), pure H_2O)

Conclusions

Our precise determination of the masses and radii of the planets allowed us to study the **interior composition of the two transiting planets.**

A best match to the mass and radius of HIP 41378 b is obtained for Earth-like core with approximately 1% of the planet's mass in a H_2 envelope. HIP 41378 c is consistent with a 2% H_2 mass envelope.

Moreover, our preliminary results suggest the presence of an **additional not-transiting planet** (**HIP 41378 g**) with a period of 56 days, close to a 7:4 resonance with planet c.



References:
Malavolta et al. 2016, A&A, 588, 118; Malavolta et al. 2018, ApJ, 155, 106; Borsato, L., Marzari, F., Nascimbeni, V., et al. 2014, A&A, 571, A38 ; Borsato, L., Malavolta, L., Piotto, G., et al. 2019, MNRAS, 484, 3233 ; Borsato et al. 2021, MNRAS, 506, 3810; Castro-González et al. 2023, A&A ,675, A52.

Email: pietro.leonardi@unitn.it