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**Characterization of exoplanetary  
systems combining transit timing  
techniques and radial velocities: From  
secular perturbations to resonant chains**

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"I may not have gone where I intended to go, but I think I have ended up where I needed to be."

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*Douglas Adams, The Long Dark Tea-Time of the Soul*

# Abstract

During the past three decades, starting from the first discovery of an exoplanet orbiting a Sun-like star in 1995, the field of exoplanetary science has evolved into a diverse and rapidly expanding discipline. In the early days, the search for new worlds dominated the field, where each new discovery opened unexplored territory of planetary science and challenged existing theories of planet formation and evolution. Today, with more than 6 000 confirmed exoplanets identified through a combination of cutting-edge ground- and space-based facilities (e.g. TESS, CHEOPS, HARPS/-N, ESPRESSO and soon PLATO) the field has entered a new era: an era focused on the detailed characterization of planetary systems and the understanding of their physical and dynamical diversity. Thanks to the continuous monitoring of modern state-of-the-art facilities, the observational baselines of many planetary systems are steadily increasing. This unprecedented temporal coverage is unlocking a new level of characterization, enabling the detection of subtle dynamical effects through timing analyses. These techniques allow to probe the gravitational and tidal interactions that shape planetary architectures and govern their long-term evolution. In this context, this thesis focuses on investigating the dynamical architecture and evolution of exoplanetary systems through complementary observational techniques. By combining Transit Timing Variations (TTVs) and high-precision Radial Velocity (RV) measurements, I provide crucial constraints on planetary masses, orbits, and system architectures. I first explored tidal orbital decay in ultra-hot Jupiters through the analysis of WASP-12 b, using 12 years of ground-based photometry to confirm its decreasing orbital period while revealing intriguing discrepancies that challenge our understanding of stellar evolution and tidal dissipation. I then focus on sub-Neptune characterization in multi-planet systems, notably focusing on the multi-planet system HIP 41378, where I performed a joint dynamical modelling of the TTV and RV signals of the two inner sub-Neptunes using extensive photometric follow-up from CHEOPS, TESS, K2, Spitzer, HST, and high-precision RVs from HARPS. This analysis dynamically confirmed the planetary nature of HIP 41378 g, a non-transiting planet with a period of about 64 days and a mass of about  $7 M_{\oplus}$ , located near a 2:1 commensurability with planet c, suggesting a possible mean-motion resonance chain in the system. Finally, I introduce a preliminary study of the young (20 Myr) multi-planet system V1298 Tau, applying a Skew-Normal fitting method to model the cross-correlation function (CCF) and mitigate stellar activity in nearly 400 HARPS-N spectra. Coupling this RV extraction with photodynamical modeling of TTVs+RVs and Gaussian process regression will enable a clearer separation of stellar and planetary signals. Altogether, this work highlights the power of combining diverse techniques to probe the complex dynamical and evolutionary pathways of exoplanetary systems.

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# 1

## Detection & characterization of exoplanetary systems

The detection and characterization of exoplanets has rapidly evolved over the past three decades, transforming our understanding of planetary systems beyond the Solar System (e.g., Mayor & Queloz 1995; Borucki et al. 2011; Perryman 2018). Thousands of planets have now been discovered ( $> 6000^1$ ), revealing an extraordinary diversity of architectures and planetary types. Among the most productive techniques are radial velocity (RV) measurements (Hatzes 2016), transit photometry (Winn 2010), and transit timing variations (TTVs) (Agol & Fabrycky 2018). Each of these methods probes different aspects of planetary systems: RVs provide planetary masses, transits yield radii and atmospheric properties, and TTVs reveal dynamical interactions and the presence of additional companions. These methods have uncovered a wide range of exoplanets, from hot Jupiters to the more common sub-Neptunes and super-Earths, as well as terrestrial planets in or near the habitable zone. Such discoveries have challenged traditional models of planet formation and highlighted the diversity of planetary systems. However, each detection technique carries inherent limitations and biases. RVs are most sensitive to massive, close-in planets; transits require favorable orbital alignments; and TTVs are only detectable in multi-planet systems with strong interactions. Therefore, combining complementary methods is crucial to achieve a comprehensive understanding of planetary systems and their formation histories.

### 1.1 Radial Velocity

The RV or Doppler method has been, and continues to be, one of the most powerful techniques for detecting and characterizing exoplanetary systems (see Fig. 1.1). This

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<sup>1</sup><https://exoplanetarchive.ipac.caltech.edu/>

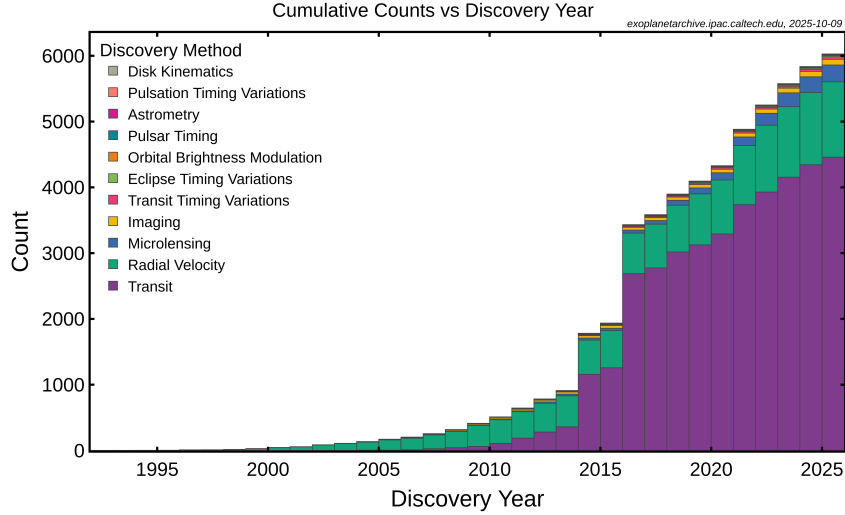


Figure 1.1: Number of exoplanet discoveries per year, grouped by detection technique. Each color represents a different detection method. Transit and RV observations have dominated exoplanet discoveries over the past decades. Data are shown up to the 30th of October 2025. Image credits: NASA Exoplanets Archive (<https://exoplanetarchive.ipac.caltech.edu>).

technique exploits the Doppler effect: when a light source moves toward the observer, its spectral lines are shifted toward shorter wavelengths (blueshift), while moving away from the observer shifts them towards longer wavelengths (redshift). In the case of a star hosting a planet, the two bodies orbit their common barycenter, causing the star to undergo a small but measurable reflex motion along the line of sight. By monitoring the star’s spectral absorption lines over time, the periodic variations in its radial velocity can be measured as:

$$v_r \approx \left( \frac{\Delta\lambda}{\lambda_{\text{em}}} \right) c, \quad (1.1)$$

where  $\Delta\lambda = \lambda_{\text{obs}} - \lambda_{\text{em}}$  is the wavelength shift relative to the rest-frame emission,  $\lambda_{\text{em}}$  is the rest wavelength, and  $c$  is the speed of light. By repeatedly measuring these tiny changes over time, one can reconstruct the radial velocity curve of the star, which encodes the presence and orbital parameters of companion bodies in the system. In practice, these variations are measured using high-resolution échelle spectrographs that provide high spectral resolving powers (i.e.  $R = \lambda/\Delta\lambda \gtrsim 70,000$ ) and extremely stable wavelength calibration systems (e.g. thorium–argon lamps, iodine cells, or laser frequency combs). Typical RV semi-amplitudes induced by planets range from hundreds of meters per second for hot Jupiters to a few centimeters per second for Earth analogues, demanding exceptional instrumental precision and long-term stability.

Assuming a Keplerian orbit, the observed stellar radial velocity as a function of time can be described as:

$$v_r(t) = K_\star [\cos(\omega + \nu(t)) + e \cos \omega] + \gamma, \quad (1.2)$$

where  $K_\star$  is the RV semi-amplitude,  $\omega$  the argument of periastron,  $\nu(t)$  the true anomaly,  $e$  the eccentricity, and  $\gamma$  the motion of the barycenter of the system. The semi-amplitude



is linked to the physical parameters of the system by (Cumming et al. 1999):

$$K_{\star} = \left( \frac{2\pi G}{P} \right)^{1/3} \frac{M_p \sin i}{(M_{\star} + M_p)^{2/3}} \frac{1}{\sqrt{1 - e^2}}, \quad (1.3)$$

where  $P$  is the orbital period,  $M_{\star}$  and  $M_p$  are the stellar and planetary masses, and  $i$  is the inclination of the orbital plane relative to the observer. Because only the line-of-sight component is measured, the inclination  $i$  could remain unknown, and the derived  $M_p \sin i$  is known as the *minimum mass* of the planet. The true mass can be recovered when  $i$  is independently constrained, for example through transit measurements (See Sec 1.2), allowing a more complete determination of the planet’s physical parameters, including its density and internal composition.

### Cross-Correlation Function method

In precise RV analyses, the cross-correlation function (CCF) method remains the standard technique for measuring Doppler shifts in stellar spectra (Queloz 1995; Baranne et al. 1996). This approach combines the information contained in thousands of stellar absorption lines by correlating the observed spectrum with a binary mask that represents the expected line pattern for a given spectral type. The binary mask itself consists of a set of narrow rectangular (“boxcar”) functions centered on the rest-frame wavelengths of well-defined absorption lines. Each line is assigned a weight proportional to its relative depth (Pepe et al. 2002). Deep and narrow lines, which have the steepest profiles, carry more Doppler information than shallow or broad ones, and are therefore given larger weights in the mask. This weighting scheme enhances the contribution of the most informative spectral features while mitigating the influence of blended or weak lines (see Fig. 1.2).

The resulting CCF can be interpreted as an average spectral line profile whose centroid provides the stellar radial velocity, while its shape parameters contain valuable diagnostics of line-profile distortions induced by stellar activity. Monitoring variations in these parameters, such as depth (contrast), width (FWHM), and asymmetry (e.g. bisector span, bi-Gauss,  $V_{\text{span}}$ ) is essential to distinguish genuine Doppler shifts caused by orbiting planets from spurious signals produced by stellar surface inhomogeneities. In most standard RV extraction pipelines, the CCF is modelled using a symmetric Gaussian function to derive the radial velocity, while asymmetries in the profile are analyzed separately through diagnostic indicators such as the bisector span,  $V_{\text{span}}$ , BIS-, BIS+, bi-Gauss, and  $V_{\text{asy}}$  (Boisse et al. 2011; Figueira et al. 2013). However, this two-step approach can limit the precision of the RV measurement in cases where the CCF exhibits significant asymmetries, often caused by strong stellar activity. An alternative method proposed by Simola et al. (2019) models the CCF with a single Skew-Normal density, which naturally accounts for both the symmetric and asymmetric components of the line profile. This approach provides, within a single fit, simultaneous estimates of the RV, the FWHM, and the degree of asymmetry (Skewness parameter), thereby offering a more self-consistent description of the stellar line profile and improved sensitivity to activity-induced distortions.

### Advantages and Limitations of the Radial Velocity Technique

Since the detection of the 4-day periodic radial-velocity signal of 51 Pegasi, with a semi-amplitude of approximately 56 m/s produced by its hot Jupiter companion (51 Pegasi b;

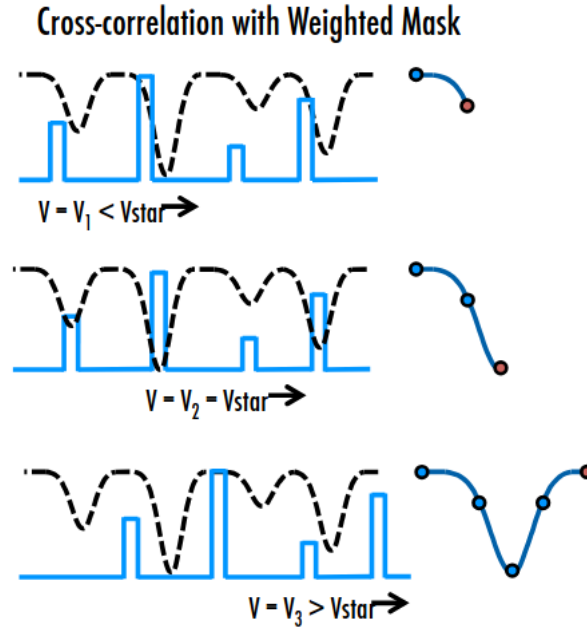


Figure 1.2: Schematic representation of the cross-correlation process using a weighted binary mask. The observed stellar spectrum (black dashed line) is correlated with a binary mask (blue) composed of boxcar functions centered on selected absorption lines. The correlation minimum occurs when the mask lines coincide with the stellar absorption lines, yielding the stellar radial velocity. Image credits: Roy et al. (2016)

Mayor & Queloz 1995), the RV technique has experienced a remarkable evolution, both in precision and in instrumental capability. Second-generation échelle optical spectrographs such as HARPS (High Accuracy Radial velocity Planet Searcher; Mayor et al. 2003) at the ESO 3.6-m telescope ( $R = 115\,000$ ) and HARPS-N on the Telescopio Nazionale Galileo (TNG) ( $R = 115\,000$ ) (Cosentino et al. 2012) achieved precisions of  $\sim 1 \text{ m s}^{-1}$ , enabling the detection of Neptune- and super-Earth-mass planets (Bouchy et al. 2009; Unger et al. 2021; Benatti et al. 2016; Malavolta et al. 2016; Mortier et al. 2018, e.g.). One of the latest state-of-the-art instruments, ESPRESSO (Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations; (Pepe et al. 2014)) at the VLT, routinely achieves sub-meter-per-second precision and aims for the  $10 \text{ cm s}^{-1}$  level required to detect true Earth analogues around nearby solar-type stars (Netto et al. 2021; Figueira et al. 2025; Hobson et al. 2025; Basant et al. 2025).

In the coming years, instruments such as ANDES (ArmazoNes high Dispersion Echelle Spectrograph; Marconi et al. 2024), one of the first-light instruments under development for the Extremely Large Telescope (ELT), are expected to achieve a long-term radial-velocity stability of about  $10 \text{ cm/s}$ . Such precision will open the possibility of probing exoplanetary atmospheres in search of biosignatures and performing accurate mass determinations of Earth-like planets.

Despite these transformative advances, the RV method remains intrinsically limited by several factors. Some of which are:

- **Unknown inclination:** only  $M_p \sin i$  can be derived without complementary data.

- **Spectral type dependence:** Cool stars with spectral types between roughly F5 and M5 are best suited for high-precision RV measurements, as they exhibit numerous and narrow absorption lines. Hotter stars ( $T_{\text{eff}} \gtrsim 10\,000$  K) possess fewer and broader spectral lines due to rotational broadening and ionization effects, while very cool stars ( $T_{\text{eff}} \lesssim 3\,500$  K) have complex molecular spectra that are difficult to model accurately.
- **Stellar activity:** Photospheric phenomena such as star spots, plages, and convective inhomogeneities (i.e. granulation), as well as stellar oscillations, can induce spurious RV shifts that mimic or mask planetary signals. These effects are particularly strong in young or magnetically active stars.
- **Instrumental stability:** Although modern spectrographs are equipped with simultaneous calibration systems (e.g. ThAr lamps, Fabry–Pérot etalons, or laser frequency combs), long-term instrumental drifts and environmental fluctuations (temperature, pressure) can still introduce systematic errors at the level of a few  $\text{cm s}^{-1}$ .

The RV remains a cornerstone of planetary characterization, particularly when combined with other techniques like transit photometry or transit time variation, it can reveal non-transiting companions (Barkaoui et al. 2025; Leonardi et al. 2025), constrain mutual inclinations, and identify resonant configurations (Leleu et al. 2024), thus playing a central role in dynamical studies of planetary systems.

## 1.2 Transit photometry

A *planetary transit* occurs when a planet’s orbital plane is aligned nearly edge-on with respect to the observer’s line of sight, causing the planet to periodically pass in front of its host star and obscure a small fraction of its light. This produces a characteristic and periodic dimming in the star’s brightness, the depth of which depends primarily on the ratio of the planet’s and star’s radii (see Figs. 1.3 and 1.4). The first exoplanet transit was detected in 2000 independently by Henry et al. (2000) and Charbonneau et al. (2000), who observed the dimming of HD 209458, a star already known to host a planet from radial-velocity measurements. This discovery provided the first direct measurement of both the radius and true mass of an exoplanet, marking the beginning of the era of transiting planet characterization and establishing the transit technique as one of the most powerful tools in exoplanetary science. However, this technique suffers from an intrinsic geometric limitation: the probability of observing a planetary transit is intrinsically low, since it requires a nearly edge-on orbital configuration ( $i \simeq 90^\circ$ ). For a planet on a circular orbit ( $e = 0$ ), this probability can be expressed as (Borucki & Summers 1984):

$$p = \frac{R_\star}{a} \simeq 0.005 \left( \frac{R_\star}{R_\odot} \right) \left( \frac{a}{1, \text{AU}} \right)^{-1}, \quad (1.4)$$

where  $R_\star$  is the stellar radius and  $a$  is the planet’s semi-major axis. This means that the likelihood of detecting a transit from an Earth-like planet orbiting a Sun-like star at 1 AU is only about 0.5%.

To overcome this limitation, large-scale surveys have been developed to monitor thousands of stars simultaneously. Space-based missions such as CoRoT, Kepler, TESS, and

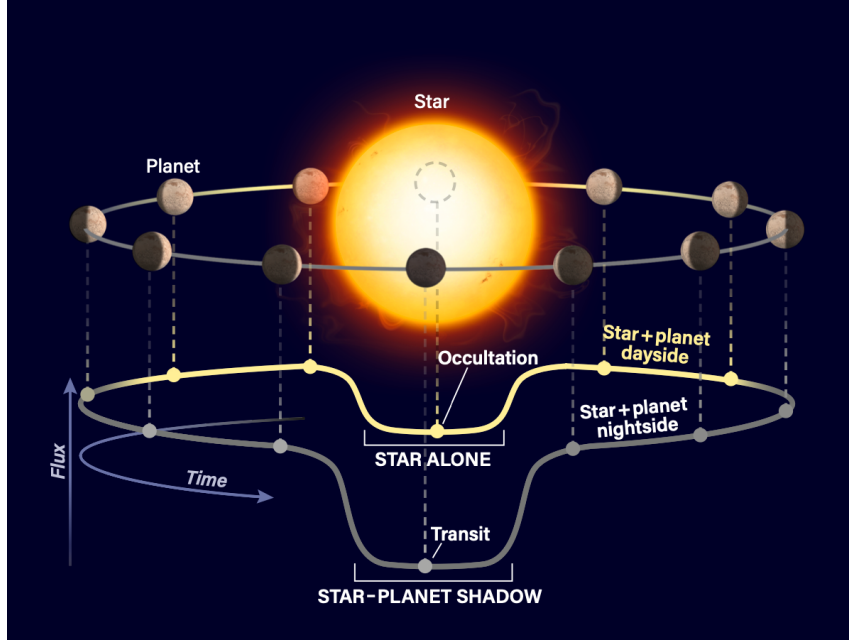


Figure 1.3: Schematic illustration of the photometric phase curve of a transiting exoplanet. The total observed flux decreases during the transit, when the planet blocks part of the stellar disk, and lightly dips again during occultation when the illuminated planetary dayside is hidden behind the star. Image credits: Astronomy: Roen Kelly

the upcoming PLATO, together with ground-based programs like HATNet, KELT, WASP, and NGTS, have revolutionized the field by continuously observing wide regions of the sky with high photometric precision. Thanks to these coordinated efforts, the transit method has become the most prolific technique for detecting and characterizing exoplanets (see Fig. 1.1). The precision achieved by modern photometry enables not only the detection of new planets but also the determination of key physical and orbital parameters such as planetary radii, orbital periods, precise transit timing (See Sec. 1.3) and, even atmospheric compositions through transmission spectroscopy.

**Geometric formulation and observables** A typical transit event can be schematically divided into four contact points: first contact (planet ingress begins), second contact (planet fully in front), third contact (egress begins), and fourth contact (planet out) (see Fig. 1.4). These points define the characteristic shape of a transit light curve and its key observables: the transit depth ( $\Delta F$ ), the orbital period ( $P$ ), the total transit duration ( $t_T$ ), and the full-transit duration ( $t_F$ ). The transit depth corresponds to the fractional loss of stellar flux during mid-transit, and, at first approximation, is given by:

$$\Delta F \simeq \left( \frac{R_p}{R_\star} \right)^2 \quad (1.5)$$

where  $R_p$  is the radius of the transiting planet and  $R_\star$  is the radius of the star. Thus, if the stellar radius is known, the transit depth directly yields the planet-to-star radius ratio and, consequently, the planetary radius. For circular orbits, the total transit duration ( $t_T$ ), measured between first and fourth contact, and the full-transit duration ( $t_F$ ), between

second and third contact, can be expressed as:

$$t_T = \frac{P}{\pi} \arcsin \left[ \frac{R_\star}{a} \sqrt{\frac{[1 + (R_p/R_\star)]^2 - [(a/R_\star) \cos i]^2}{1 - \cos^2 i}} \right], \quad (1.6)$$

$$t_F = \frac{P}{\pi} \arcsin \left[ \frac{R_\star}{a} \sqrt{\frac{[1 - (R_p/R_\star)]^2 - [(a/R_\star) \cos i]^2}{1 - \cos^2 i}} \right], \quad (1.7)$$

where  $a$  is the orbital semi-major axis and  $i$  is the inclination of the orbital plane. Following the formulation of Seager & Mallén-Ornelas (2003), for a planet on a circular orbit, the impact parameter  $b$ , defined as the projected distance between the centers of the star and the planet at mid-transit, expressed in units of stellar radii, can be written as:

$$b = \frac{a}{R_\star} \cos i = \left\{ \frac{(1 - \sqrt{\Delta F})^2 - [\sin^2(\pi t_F/P)/\sin^2(\pi t_T/P)] (1 + \sqrt{\Delta F})^2}{\cos^2(\pi t_F/P)/\cos^2(\pi t_T/P)} \right\}^{1/2}. \quad (1.8)$$

The impact parameter determines the geometry of the transit: central transits ( $b \approx 0$ ) produce deep, symmetric light curves, while grazing transits ( $b \rightarrow 1$ ) result in shorter, shallower events (see Fig. 1.4). From the same geometric relations, the scaled semi-major axis can be expressed as:

$$\frac{a}{R_\star} = \sqrt{\frac{(1 + \sqrt{\Delta F})^2 - b^2}{\sin^2(\pi t_T/P)}} \quad (1.9)$$

and combining Kepler's third law:

$$\frac{a^3}{P^2} = \frac{G(M_\star + M_p)}{4\pi^2}, \quad (1.10)$$

and assuming  $M_p \ll M_\star$ , allows one to infer the mean stellar density directly from the transit light curve as:

$$\rho_\star = \frac{3\pi}{GP^2} \left( \frac{a}{R_\star} \right)^3 \quad (1.11)$$

This relation shows how the transit light curve measurements alone can give information on the physical parameters of the host star and help validate the planetary nature of the event.

By the same token, when transit observations are combined with parameters derived from the spectroscopic radial velocity motion of the planet, the planetary surface gravity ( $g_p$ ) can be computed. This provides a fundamental constraint on the planet's bulk composition and is important in assessing a planet's potential for atmospheric transmission spectroscopy (Southworth et al. 2007). The mass function of a spectroscopic binary is defined by (Hilditch 2001):

$$f(M_p) = \frac{(1 - e^2)^{3/2} K_\star^3 P}{2\pi G} = \frac{M_p \sin^3 i}{(M_\star + M_p)^2}. \quad (1.12)$$

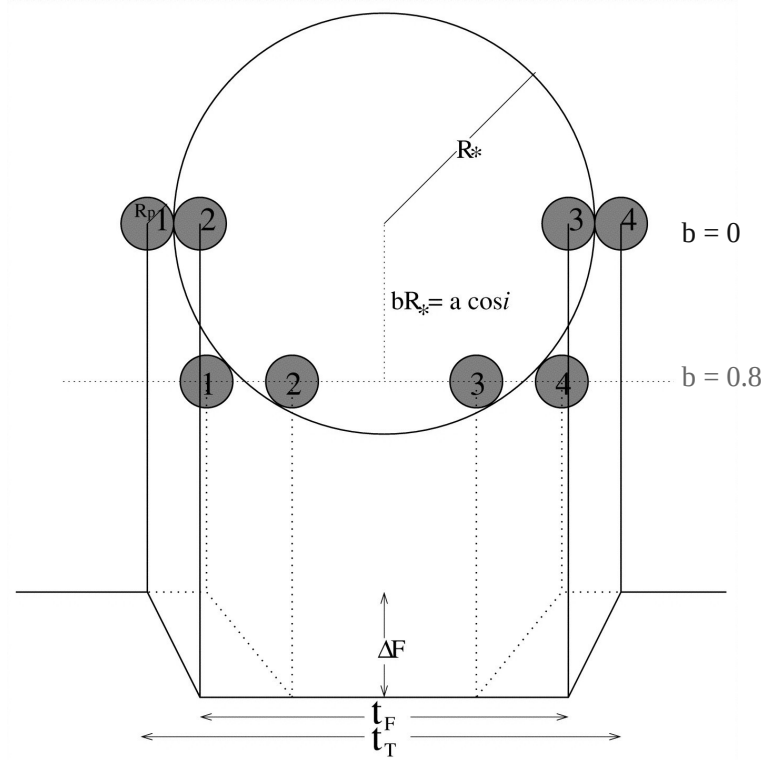


Figure 1.4: Illustration of an observable transit light curve, showing the depth, durations, and the four points of contact. Two light curves are shown for two impact parameters  $b$ . Image credit: Seager & Mallén-Ornelas (2003)

When combined with Kepler's third law 1.10, and the definition of surface gravity ( $\frac{GM_p}{R_p^2}$ ), the equation can be rearranged to solve for  $g_p$  using only directly observable quantities:

$$g_p = \frac{GM_p}{R_p^2} = \frac{2\pi}{P} \frac{(1 - e^2)^{3/2} K_\star}{(R_p/a)^2 \sin i} \quad (1.13)$$

## Limb Darkening

These analytical expressions assume a uniform surface brightness. In reality, stellar disks are brighter in the middle and become fainter as they get closer to the edge. This effect arises because the star's atmosphere is not isothermal and not of infinite optical depth. When observing closer to the edge (limb), the line of sight penetrates only the upper, cooler layers of the stellar photosphere. Near the center, the observer sees deeper and thus hotter, brighter material. This effect significantly modifies the shape of the transit light curve, making the ingress and egress more gradual and the transit bottom slightly rounded, and must therefore be accurately modeled to derive precise planetary and stellar parameters.

## Combining Techniques: Direct determination of the surface gravities of transiting extrasolar planets

### 1.3 Transit Time Variations

A planet on an unperturbed Keplerian orbit should exhibit transits at perfectly regular intervals, corresponding to a constant orbital period. However, observed deviations from strict periodicity, known as TTVs, indicate that additional dynamical effects are at play. These variations arise primarily from gravitational perturbations induced by other planets in the system (Multi-planet interactions) or from strong star–planet interactions that modify the orbital motion over hundreds or thousands of years (Secular perturbations, e.g. Agol et al. 2005; Holman & Murray 2005; Ragozzine & Wolf 2009). These two mechanisms produce TTVs on different characteristic timescales. Interactions with nearby planets typically generate sinusoidal TTV signals that are detectable over the course of a few to several orbital cycles. In contrast, secular perturbations gradually alter the orbital elements of a planet, such as its semi-major axis, eccentricity, or argument of pericenter, on much longer timescales, ranging from decades to millennia. Beyond planet–planet or star–planet interactions, TTVs have also been proposed as a method to detect exomoons, whose gravitational influence on the host planet can introduce subtle but measurable deviations in the observed transit times (Sartoretti & Schneider 1999; Kipping 2009a, 2009b; Fox & Wiegert 2021).

When measured with sufficient precision, TTVs can be applied to several areas of exoplanet research and provide a powerful diagnostic tool to infer planetary masses, eccentricities, planetary interior structure, and orbital configurations, sometimes even revealing non-transiting companions that would otherwise remain undetected. The concept behind this technique dates back to the nineteenth century: Neptune was discovered by observing its gravitational effects on Uranus and calculating its mass and position through inverse dynamical modeling (Adams 1846). The first significant detection of TTVs in an exoplanetary system was achieved with the high-precision photometry of the Kepler mission, in the multiple-transiting system Kepler-9 Holman et al. (2010). Shortly thereafter, the first detection of TTVs induced by a non-transiting planet was reported in the Kepler-19 system (Ballard et al. 2011). In this case, the transiting Saturn-sized planet Kepler-19 b exhibits timing variations of approximately five minutes, attributed to the gravitational perturbations of a non-transiting companion, Kepler-19 c, located near a resonant period ratio with the transiting planet.

#### Linear ephemeris and O-C diagram

During a planetary transit, the instant when the center of the planet’s disk passes across the projected center of the stellar disk is defined as the mid-transit time ( $T_{\text{mid}}$ ). For a strictly periodic orbit, the sequence of mid-transit times can be described by a simple linear ephemeris:

$$T_E = T_{\text{ref}} + P \times E, \quad (1.14)$$

where  $E$  is the transit number (or epoch),  $T_{\text{ref}}$  is the reference mid-transit time at epoch  $E = 0$ , and  $P$  is the orbital period. To identify and characterize deviations of the observed transit times ( $T_{\text{obs}}$ ) from the predicted linear ephemeris ( $T_E$ ), one constructs the so-called

Observed minus Calculated (O–C) diagram. This diagram provides a direct visualization of transit timing variations (TTVs), where

$$O - C = T_{obs} - T_E, \quad (1.15)$$

plotted as a function of transit epoch ( $E$ ) or time. An example of a simulated O–C diagram is shown in Fig. 1.5, which illustrates how deviations from a linear ephemeris manifest as systematic trends or periodic variations in the residuals.

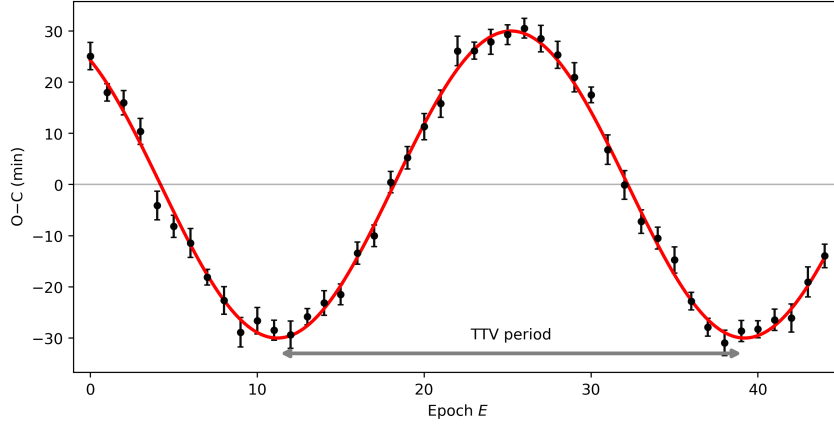


Figure 1.5: Example of a simulated short-term TTV signal. The black points with error bars represent the observed minus calculated (O–C) transit times for a transiting planet as a function of epoch. The red curve shows the best-fitting sinusoidal model describing the periodic deviations from a constant ephemeris. The double arrow indicates the TTV period, corresponding to the time between two consecutive extrema of the signal. The amplitude of the variations ( $\sim 30$  minutes) is typical of systems experiencing strong gravitational interactions with a nearby companion in or near mean-motion resonance.

### 1.3.1 Secular perturbations

Secular perturbations are long-term, cumulative effects arising from gravitational, tidal, rotational, and relativistic effects in planetary systems. These phenomena predominantly concern close-in exoplanets, most famously hot Jupiters, orbiting very near their stars. Unlike short-term planet-planet interactions, secular changes often affect the orbital elements of a planet (such as its semi-major axis, impact parameter, eccentricity, inclination, or longitude of periastris) on a timescale two or three orders higher than the orbital period of the planet. Two prominent effects of secular TTVs are orbital decay (shrinking of the semi-major axis, usually driven by tidal dissipation) and apsidal precession (rotation of the apsidal line).

Secular variations in transit timings can also arise from other effects like the light-travel time effect (LTTE), also known as “Rømer delay”, due to the reflex motion of the host star; in order to unambiguously distinguish between these different origins of long-term TTVs, complementary radial-velocity measurements are essential (Yee et al. 2019; Winn & Stefánsson 2025).



## Orbital decay

When the stellar rotation period exceeds the orbital period of a close-in planet, tidal interactions drive orbital decay. In this regime, the tidal bulge raised on the star by the planet lags behind the orbital motion, resulting in a net torque that transfers orbital angular momentum from the planet to the stellar spin. The planet's orbital energy is dissipated through tides, gradually spinning up the host star while being deposited within the stellar tidal bulge (Zahn 1977; Hut 1981; Eggleton et al. 1998). As the orbital separation (and thus the semi-major axis) decreases, the planet ultimately approaches the stellar Roche limit. This leads to Roche-lobe overflow (RLO), a process which the gas giant begins losing part of its mass. The final outcome of this process depends heavily on the core mass ( $M_c$ ) of the overflowing planet (Valsecchi et al. 2014, 2015; Jackson et al. 2016; Ginzburg & Sari 2017): i) Light core ( $M_c < 6M_\oplus$ ): The planet loses only a portion of its envelope, leaving behind a remnant gas-rich, lower-mass planet ii) Dense core ( $M_c > 6M_\oplus$ ): The planet is fully stripped of its gaseous envelope. While the resulting exposed core may eventually be engulfed by the host star (Levrard et al. 2009), this scenario provides a compelling explanation for the population of Earth-sized Ultra-Short-Period (USP) planets. These planets, with orbital periods  $P < 1$  day, may represent the surviving remnant cores of Hot Jupiters (HJs) that have lost their entire atmospheres.

Studies on the occurrence rate of giant planets (Miyazaki & Masuda 2023), together with analyses of the Galactic velocity dispersion of their host stars (Hamer & Schlaufman 2019), showed that HJs tend to orbit predominantly younger stars when compared to the general field star population. This trend suggests that HJs are destroyed by tidal orbital decay while their host stars are still on the main sequence.

From an observational point of view, the effect of orbital decay results in a parabolic trend in the O–C diagram, both for transit and occultation times, since the gradual shortening of the orbital separation causes the observed events to occur progressively earlier than predicted by a constant-period ephemeris (Yee et al. 2019). In this case, the sequence of mid-transit times is better described by a quadratic model, following Eq (4) of Yee et al. (2019):

$$T_E = T_{\text{ref}} + P \times E + \frac{1}{2} \frac{dP}{dE} \times E^2 \quad (1.16)$$

where  $E$ ,  $T_{\text{ref}}$ , and  $P$  are the transit epoch, the reference mid-transit time, and the orbital period, respectively, while  $dP/dE$  represents the change in the orbital period between succeeding transits. In this scenario, the curvature of the parabola directly reflects the rate of orbital decay, allowing one to provide critical insights into the remaining lifetime of the close-in planet by computing the characteristic orbital decay timescale as

$$\tau_{\text{decay}} = \frac{P}{|\dot{P}|}, \quad (1.17)$$

where  $\dot{P}$  is the time derivative of the orbital period.

Multiple exoplanetary systems have provided evidence for orbital decay, however, as of now, the only confirmed case is WASP-12b (Yee et al. 2019; Turner et al. 2021; Wong et al. 2021; Leonardi et al. 2024), a hot Jupiter with a 1.09-day orbital period. For a more in-depth analysis of this system and the observational confirmation of its orbital decay, I refer the reader to Chapter 2.

## Apsidal Precession

Apsidal precession refers to the gradual rotation of the apsidal line, which connects the aphelion and perihelion of an orbit, within the orbital plane (Giménez & Bastero 1995). This phenomenon is driven by several factors, including stellar and planetary quadrupole moments (due to oblateness), general relativistic effects, tidal interactions between the planet and its host star, and perturbations from other planets.

Therefore, the total rate of apsidal precession can be written as:

$$\dot{\omega}_{\text{tot}} = \dot{\omega}_{\text{tid,p}} + \dot{\omega}_{\text{gr}} + \dot{\omega}_{\text{rot,p}} + \dot{\omega}_{\text{rot},\star} + \dot{\omega}_{\text{tid},\star} + \dot{\omega}_{\text{p2}}. \quad (1.18)$$

Ragozzine & Wolf (2009) demonstrated that for hot Jupiters ( $P < 10$  days,  $T_{\text{eq}} > 1000$  K), the dominant term to the theoretical precession rate of periastron comes from the planet's tidal deformation ( $\dot{\omega}_{\text{tid,p}}$ ), exceeding the effects of general relativity ( $\dot{\omega}_{\text{gr}}$ ) and the quadrupole field ( $\dot{\omega}_{\text{rot,p}}, \dot{\omega}_{\text{rot},\star}$ ) by 1-2 orders of magnitude.

For hot Jupiters, the planet's proximity to the host star raises a substantial tidal bulge on the smaller body, resulting in a significant gravitational potential and, consequently, substantial apsidal precession (see Fig. 1.6). The apsidal precession rate due to the planet's tidal bulge is given by Ragozzine & Wolf (2009) (Eq. 6):

$$\dot{\omega}_{\text{tid,p}} = \frac{15}{2} k_{2,p} \left( \frac{R_p}{a} \right)^5 \frac{M_\star}{M_p} f_2(e) n \quad (1.19)$$

where  $n$  is the mean motion and  $f_2(e)$  is an eccentricity function.

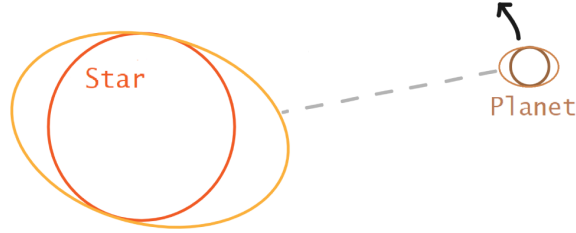


Figure 1.6: Geometric visualization of the star-planet system under tidal interactions. The unperturbed spherical shapes are shown in red and dark brown, while the tidal bulges, in orange and light brown, are elongated towards the other body. Adapted from Bernabò et al. (2024).

This effect can be described as a long-period sinusoidal trend that follows the model (Giménez & Bastero 1995; Patra et al. 2017):

$$t_{\text{tra}}(E) = t_0 + P_s E - \frac{e P_a}{\pi} \cos \omega \quad (1.20)$$

where

$$\omega(E) = \omega_0 + \frac{d\omega}{dE} E, \quad (1.21)$$

$$P_s = P_a \left( 1 - \frac{1}{2\pi} \frac{d\omega}{dE} \right). \quad (1.22)$$

Here,  $t_0$  is the reference time,  $e$  is the orbital eccentricity,  $\omega$  is the argument of pericenter,  $P_a$  is the anomalistic period, and  $P_s$  is the sidereal period.

By fitting observed transit timing variations to this precession model, we can obtain precise constraints on the apsidal precession rate,  $\frac{d\omega}{dE}$ . This, in turn, enables the determination of the planetary Love number,  $k_{2,p}$ .

The Love number is a dimensionless parameter that quantifies a planet’s response to tidal and rotational forces, contributing to the gravitational quadrupole through the induced tidal and rotational bulges. It provides crucial insights into the internal structure of hot Jupiters, particularly the degree of differentiation between their internal layers. Ragozzine & Wolf (2009) demonstrated that the apsidal precession rate is directly proportional to  $k_{2,p}$  (see Eq. 1.19). Measuring  $k_{2,p}$  through apsidal precession therefore allows us to probe a planet’s internal structure, including core size and the distribution of material within the envelope.

Accurate determinations of  $k_{2,p}$  for hot Jupiters can discriminate between competing planetary composition models, constraining key factors such as core mass and metallicity. This approach has already been applied in studies of systems such as HAT-P-13b (Buhler et al. 2016), WASP-121b (Wahl et al. 2021), WASP-103b (Barros et al. 2022), and WASP-19b (Bernabò et al. 2024).

**Eccentric hot Jupiters** are believed to form through dynamic evolutionary processes, with high-eccentricity tidal migration being a leading hypothesis to explain their current orbital configurations. Through mechanisms such as planet-planet scattering, Kozai-Lidov cycles, and tidal circularization, these planets are driven into highly eccentric orbits before eventually migrating inward to their present-day short-period orbits (see, e.g., Rasio et al. 1996, Fabrycky & Tremaine 2007, Dawson & Johnson 2018). These extreme orbits provide an ideal environment for observing pronounced apsidal precession effects, making them excellent candidates for studying these dynamic interactions with their host stars. Eccentric hot Jupiters undergo stronger tidal forces and more complex interactions because their elongated orbits create varying gravitational potentials, driven by the changing size of the tidal bulge throughout the orbital period.

The photometric detectability of apsidal precession is strongly tied to the eccentricity of the system. In circular orbits, apsidal motion is unobservable. Additionally, when eccentricity is poorly constrained, accurately measuring the argument of periastron becomes challenging. Detecting precession through transit light curves is difficult, often leading investigators to assume circular orbits. However, this does not necessarily mean the orbit is truly circular, but it only places an upper limit on eccentricity (Bernabò et al. 2024).

While slightly eccentric hot Jupiters ( $0 < e < 0.1$ ) are expected to experience apsidal precession, the timescales are on the order of centuries (Ragozzine & Wolf 2009). In contrast, these effects are much more pronounced in moderately eccentric systems ( $e > 0.1$ ), potentially causing observable long-term variations in the apparent orbital period in less than 10 years.

### 1.3.2 Multi-Planet Interactions

In multi-planet systems, gravitational interactions between neighboring planets can lead to an exchange of energy and angular momentum, producing measurable shifts in their transit times. In this scenario, the TTV signal of a transiting planet arises solely from the gravitational perturbations of its companion, and therefore depends on the mass and

orbital properties (i.e. period, the planet-to-star mass ratio, eccentricity, and semi-major axis) of the perturber rather than on those of the transiting planet itself.

In a two-planet configuration, the TTV (or O-C) signal of the transiting planet can be expressed following Eq. 6 of Agol & Fabrycky (2018):

$$\delta t_1 = P_1 \frac{m_2}{M_\star} f_{12}(\alpha_{12}, \theta_{12}), \quad (1.23)$$

where  $P_1$  is the orbital period of the transiting planet,  $m_2$  is the mass of the perturbing companion, and  $M_\star$  is the stellar mass. The functions  $f_{ij}$  is a function of the semi-major axis  $\alpha_{12}$ , and of  $\theta_{12}$  which represents the relevant orbital elements (see also Lithwick et al. 2012, Deck & Agol 2016).

Dynamical simulations suggest that the amplitude of TTVs in typical planetary systems is generally quite small, often ranging from seconds to minutes (Holman & Murray 2005). An exception to this occurs when planets are located in, or near, mean-motion resonances (MMR), where the gravitational perturbations are strongly amplified. In such configurations, the TTV amplitude can increase by orders of magnitude, reaching several hours to days, making them readily detectable with current photometric precision (Agol et al. 2005; Lithwick et al. 2012).

### Mean Motion Resonances

A system of two planets is said to exhibit commensurability if the ratio of the orbital periods of two planets is close to a ratio of small integers. Such commensurabilities often signal that the planets are located in, or near, a mean-motion resonance (MMR). Resonances are typically denoted as  $P_1 : P_2 = j : k$  MMRs, with 1, 2 referring to the inner and outer planes, respectively. The order of the resonance is given by  $|j - k|$ , where  $j - k = 1, 2$ , and 3 correspond to first-, second-, and third-order resonances, respectively. Following Lithwick et al. (2012), for two planets close to a MMR, we can compute the TTV period ( $P_{\text{TTV}}$  or super-period), defined as:

$$P_{\text{TTV}} = \frac{1}{|j/P_2 - k/P_1|} \quad (1.24)$$

and the normalized distance from the exact resonance ( $\Delta$ ), also called resonance offset:

$$\Delta = \frac{P_2/P_1}{j/k} - 1. \quad (1.25)$$

There is, however, no single threshold value of  $\Delta$  that uniquely confirms whether a system is resonant. Instead,  $\Delta$  simply quantifies the proximity of a planet pair to an exact commensurability. To understand if two planets are in a MMR configuration, we need additional dynamical information, such as the libration of the resonant angles. By integrating the orbits of the system over a sufficient timescale, we can track the evolution of the corresponding resonant angles (or arguments):

$$\phi_{1,2} = j\lambda_1 - (j+k)\lambda_2 + \varpi_{1,2} \quad (1.26)$$

where  $\varpi = \omega + \Omega$  is the longitude of the pericentre and  $\lambda$  represents the mean longitude. They are a measure of the displacement of the longitude of conjunction from the pericentre

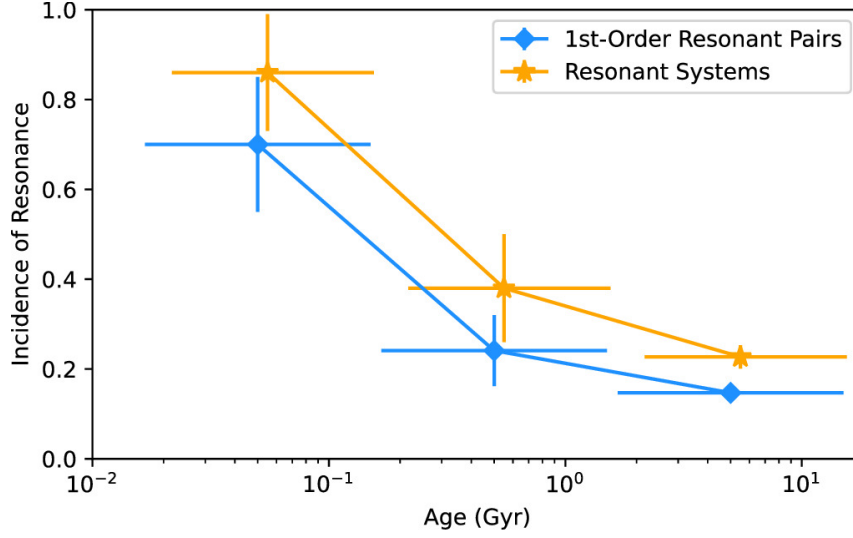


Figure 1.7: Plot displaying the incidence of observed first-order resonant pairs (blue curve) and the incidence of planetary systems with at least one resonant pair (first-or second-order; orange curve) across ages. Image credits: Dai et al. (2024)

of the outer planet. If at least one of these angles librates (i.e., oscillates around a fixed value) rather than circulating through  $0-2\pi$ , the system is considered to be in resonance. As shown by Hadden & Lithwick (2017), even pairs with  $\Delta < 0.01$  (thus within 1%) of a first-order MMR do not show librating resonant arguments.

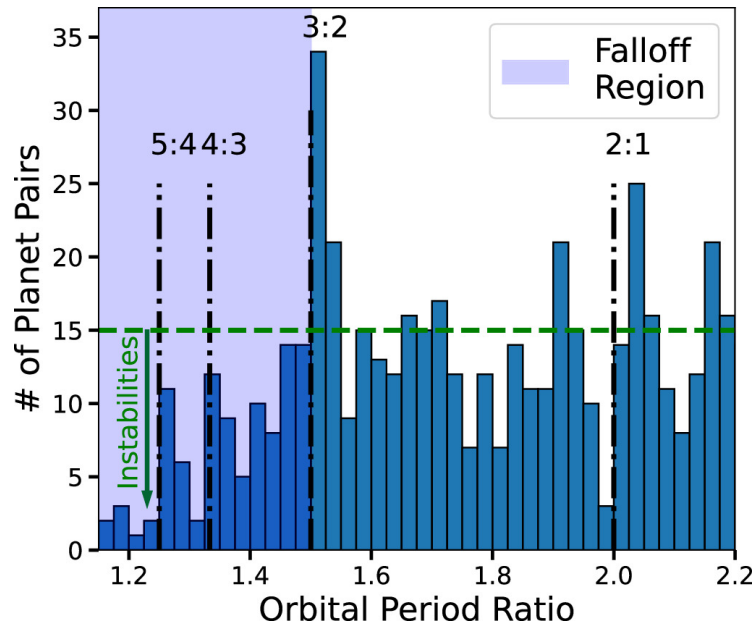


Figure 1.8: Histogram showing the period ratios of adjacent exoplanets. Image credits: Chen et al. (2025)

Orbital resonances serve as a dynamical hallmark of planetary system evolution, often tracing their origins to gravitational interactions within protoplanetary disks (Melita &

Woolfson 1996; Lee & Peale 2002; Cresswell & Nelson 2006). According to theoretical models, configurations in or near MMRs are expected to form during the early stages of planetary system evolution, when planets are captured into resonance chains as a consequence of Type-I convergent migration within the gas-rich protoplanetary disk (Malhotra 1993a; Kley & Nelson 2012; Delisle 2017; Tamayo et al. 2017; Izidoro et al. 2017; MacDonald & Dawson 2018). A notable example is PDS 70, a young system ( $\sim 5$  Myr) where two directly imaged protoplanets embedded in the protoplanetary disk are near resonance (Bae et al. 2019; Benisty et al. 2021), and recent evidence suggests a third candidate forming a potential 4:2:1 resonant chain (Hammond et al. 2025).

Despite these theoretical predictions, there is a tension between disk migration simulations and the observed architectures of planetary systems. While migration models predict a high occurrence of planetary systems locked in resonance chains, only a small fraction of observed systems appear to be in such configurations. In fact, the majority of mature ( $>1$  Gyr) Kepler and TESS multi-planet systems are found to be non-resonant (Huang & Ormel 2023). At the same time, the distribution of observed multi-planet systems shows a statistically significant excess of adjacent planet pairs with period ratios close to first-order commensurabilities (i.e.,  $j : j + 1$ ) (see Fig. 1.8; Fabrycky et al. 2014; Dai et al. 2024; Chen et al. 2025). In particular, Dai et al. (2024) demonstrated that this excess is especially pronounced among young, close-in planets (see Fig. 1.7), supporting the prediction of Hamer & Schlaufman (2024) that resonant chains may be far more common during the early stages of planetary system evolution.

This apparent discrepancy can be explained by the “breaking the chains” model, in which planetary systems that were captured into MMRs during their early evolution later undergo dynamical instabilities following disk dispersal. These instabilities may arise from overstable libration driven by post-disk eccentricity damping (Goldreich & Schlichting 2014; Xu & Lai 2017, e.g. tides;), planetesimal scattering (Chatterjee et al. 2016; Wu et al. 2024), divergent migration during disk dispersal (Liu et al. 2022; Hansen et al. 2024), secular chaos (Petrovich et al. 2019), or global orbital instabilities (Pu & Wu 2015; Izidoro et al. 2017; Goldberg et al. 2022). These processes can disrupt the initial resonant configurations, displacing planets slightly away from exact commensurabilities (Izidoro et al. 2017, 2021; Carrera et al. 2019; Esteves et al. 2023; Goldberg & Batygin 2023; Weiss et al. 2023).



# 2

## A new ground-based investigation of orbital decay in the ultra-hot Jupiter WASP-12b

**Foreword:** The discovery of the first transiting hot Jupiters (HJs), giant planets on orbital periods shorter than  $P \sim 10$  days, was announced more than 20 years ago. As both ground- and space-based follow-up observations are piling up, we are approaching the temporal baseline required to detect secular variations in their orbital parameters. In particular, several recent studies have focused on constraining the efficiency of the tidal decay mechanism to better understand the evolutionary timescales of HJ migration and engulfment. This can be achieved by measuring a monotonic decrease in orbital period  $dP/dt < 0$  due to mechanical energy being dissipated by tidal friction. WASP-12 b was the first HJ for which a tidal decay scenario appeared convincing, even though alternative explanations have been hypothesized. Here we present a new analysis based on 28 unpublished high-precision transit light curves gathered over a 12-year baseline and combined with all the available archival data, and an updated set of stellar parameters from HARPS-N high-resolution spectra, which are consistent with a main-sequence scenario, close to the hydrogen exhaustion in the core. Our values of  $dP/dt = -30.72 \pm 2.67$  and  $Q'_* = (2.13 \pm 0.18) \times 10^5$  are statistically consistent with previous studies, and indicate that WASP-12 is undergoing fast tidal dissipation. We additionally report the presence of excess scatter in the timing data and discuss its possible origin.

Based on:

Leonardi P., et al. 2024, *Astronomy and Astrophysics*, 686, A84 (2024). <https://doi.org/10.1051/0004-6361/202348363>



## 2.1 Introduction:

The discovery of Jupiter-sized extrasolar planets orbiting their host stars at unexpectedly close distances known as hot Jupiters (HJs) posed several new questions about planetary formation and planet migration theories. Over the last two decades, astronomers have taken important steps to understand how HJs originated. To date, the main process thought to be responsible for such short orbits is migration from their formation site farther out (Dawson & Johnson 2018; Fortney et al. 2021). The two most accredited transport mechanisms are disk-driven migration, due to friction with the gaseous disk around the young star (Lin et al. 1996; Nelson et al. 2000), and high-eccentricity migration (HEM), through planet-planet scattering (Rasio et al. 1996) or secular interactions (Fabrycky & Tremaine 2007; Wu & Lithwick 2011). If we consider the current occurrence estimates of one planet (to or for) every two stars in the Milky Way (Howard et al. 2012; Dressing & Charbonneau 2013; Batalha et al. 2013; Silburt et al. 2015), it is clear that only a tiny fraction of the total exoplanet population has been detected and studied. The many planetary systems identified so far range in size from tiny rocky planets to massive gas giants, and show us that diversity is one of the most important aspects of exoplanet demographics. In recent years a new subclass of HJs has emerged, known as ultra-hot Jupiters (UHJs); they have day-side temperatures higher than 2200 K (Parmentier et al. 2018) and orbital periods between  $\lesssim 1$  day and  $\sim 2$  days. Given their extreme properties, they are valuable test cases for probing atmospheric chemistry (Stangret et al. 2022), understanding planetary mass loss, and constraining planetary formation and evolution models.

WASP-12b, the subject of this study, is one of these UHJs ( $T_{\text{eq}} \approx 2600$  K). Discovered in 2009 by Hebb et al. (2009), as part of the Wide-Angle Search for Planets (WASP) project, WASP-12b is known to be inflated ( $R_p = 1.825 \pm 0.091 R_{\text{jup}}$ ;  $M_p = 1.39 \pm 0.12 M_{\text{jup}}$ ) and orbiting an F-type star ( $T_{\text{eff}} = 6250$  K) with a small projected rotational velocity ( $v \sin i = 2.2 \pm 1.5$  km/s, Albrecht et al. 2012) in  $P \approx 1.09$  days. The peculiar architecture of WASP-12b has inspired several research studies on its atmosphere and planet-star interactions. Strong absorption lines of metals in the near-UV spectra were revealed by the Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope (Fossati et al. 2010; Haswell et al. 2012; Nichols et al. 2015). Optical transit measurements revealed that the planet is inflated, and infrared phase curves showed that it is filling  $\sim 84\%$  of its Roche lobe resulting in high mass-loss rates of metals and heavy elements (Lai et al. 2010; Li et al. 2010; Bell et al. 2019; Antonetti & Goodman 2022). An escaping exosphere was suggested as the cause of these phenomena (Li et al. 2010; Fossati et al. 2010; Haswell et al. 2012). According to hydrodynamic simulations by Debrecht et al. (2018), a circumstellar disk is forming due to the expanding exospheric gas that overfills the Roche lobe and escapes via the Lagrangian L1 and L2 points. Finally, a new atmospheric model also including the formation of  $\text{H}^-$  through dissociation of  $\text{H}_2\text{O}$  and  $\text{H}_2$  has been proposed by Himes & Harrington (2022) to reconcile the previous findings.

Another notable feature of WASP-12b is its changing orbital period. A single planet on an unperturbed Keplerian orbit should transit at regular intervals; in other words, it should have a perfectly constant orbital period. If the transits are no longer strictly periodic, among the possible causes for this perturbation are the presence of additional bodies in the system, tidal forces and relativistic effects (e.g., Agol et al. 2005; Holman & Murray 2005; Antoniciello et al. 2021). On close-in planets, tidal effects can cause orbital circularization

and a change in orbital period (Rasio et al. 1996; Levrard et al. 2009). Since the early days of exoplanet research (Rasio et al. 1996; Sasselov 2003), it has already been suggested that short-period planets could be unstable due to tidal dissipation. Detection of orbital decay is now within reach because many transiting exoplanets, predominantly HJs, have been monitored for decades, using both space- and ground-based surveys, as part of long-term transit-timing observation campaigns.

The first claim of short-term period variations in WASP-12b was published by Maciejewski et al. (2011), and was interpreted as being due to the dynamical perturbation from an unseen planetary companion (called Transit Time Variations, TTVs). This detection prompted other observational campaigns to confirm and assess the cause of this signal. Maciejewski et al. (2016) published additional data and discovered a quadratic trend in the  $O - C$  diagram of the mid-transit timing compatible with a uniformly decreasing orbital period. Subsequent studies validated this finding (Patra et al. 2017; Collins et al. 2017; Maciejewski et al. 2018; Baluev et al. 2019), which might be equally explained by 1) an orbital shrinkage related to tidal decay or 2) the Rømer effect from an unseen companion or 3) part of a long-term ( $\approx 14$  yrs) oscillation generated by apsidal orbital precession. The third hypothesis is plausible if the eccentricity is  $e \approx 0.002$ . However, due to the expected fast rate of tidal circularization, it is unclear how to retain such an eccentricity (Weinberg et al. 2017). Yee et al. (2019) presented compelling evidence against apsidal precession and the Rømer effect as major contributors. The authors demonstrated how the  $O - C$  values of the occultations have a decreasing pattern compatible with that of the  $O - C$  values of the transits, while the mid-transits and occultation are expected to exhibit an opposite trend when the apparent orbital period variation is due to the apsidal precession. Furthermore, their study revealed no significant acceleration of the barycenter of the system along the line of sight using radial velocity observations, disproving the Roemer effect as the primary cause of the observed decreasing  $O - C$  trend. This supported the orbital decay scenario, further confirmed by the two latest studies on this system from the TESS space telescope primary and extended missions: Turner et al. (2021) and Wong et al. (2022). The latter research derived a value for the period change rate  $dP/dt = -29.81 \pm 0.94$  ms/yr by including transit and secondary eclipse light curves.

In this work we present 28 unpublished, high-precision, ground-based light curves of WASP-12b. Additionally, we analyze high-resolution optical spectra from the High Accuracy Radial velocity Planet Searcher in the Northern hemisphere (HARPS-N, Cosentino et al. 2012; 2014) at the Telescopio Nazionale Galileo (TNG) in La Palma, in order to derive the stellar parameters of the host star and improve the calculation of the tidal quality factor. In Section 2.2 of this work, we present the new photometric and spectroscopic observations and our data reduction procedures. In Section 2.3, we describe the data analysis. The results of the timing analysis aimed at computing the orbital period change rate and constraining the stellar tidal quality factor  $Q'_*$  are reported in Section 2.4. Finally, in Section 2.5 we present a summary of our conclusions.

## 2.2 Observations and data reduction

### 2.2.1 Photometry

The unpublished photometric observations we present were gathered by the TASTE project, a long-term observing program aimed at monitoring transiting planets and creating a library of high-precision light curves to exploit the TTV technique (Nascimbeni et al. 2011; Granata et al. 2014). The project is mostly based on the Asiago Astrophysical Observatory located at Mount Ekar (elevation: 1366 m) in northern Italy, plus other medium-class telescopes around the globe. The Asiago facilities include the 1.82m Copernico telescope, a Cassegrain telescope equipped with the Asiago Faint Object Spectrograph and Camera (AFOSC) with a  $8.8 \times 8.8$  arcmin<sup>2</sup> field of view, which acquired all but one of our light curves. The AFOSC detector is a back-illuminated  $2048 \times 2048$  E2V pixels CCD. The remaining light curve was obtained at the 67/92 cm Schmidt telescope at the same observatory. Our observing strategy is based on defocusing the images and applying differential photometry techniques to minimize the impact of systematic errors from instrumental and telluric sources. For all observations, we adopted for consistency the same set of two reference stars (TYC 1891-38-1 and TIC 86396443), always imaged over the years in the field of view of the telescope. There are no known variability indicators or higher-than-expected photometric scatter in any of them. A complete description of the TASTE observing strategy and data reduction software is given by Nascimbeni et al. (2011, 2013).

Our 28 transit light curves were collected over 12 years (2010-2022); a detailed observing log is reported in Table 2.1, summarizing the dates and other relevant information. All the images were acquired either with a standard Cousins  $R_C$  filter ( $\lambda_{\text{eff}} = 672.4$  nm) or a standard SDSS  $r'$  ( $\lambda_{\text{eff}} = 620.4$  nm), both chosen to maximize the atmospheric extinction and limb darkening effects. The advantage of observing in the  $R_C$  or  $r'$  passbands is that the impact of the limb-darkening on the transit profile is reduced with respect to the V passband, thus the timing of the ingress and egress is improved. Moreover, extinction in the Earth's atmosphere is also reduced by observing in those passbands. We applied windowing and  $4 \times 4$  binning to increase the duty cycle of the series as much as possible, while keeping our reference stars within the imaged field. Stars were intentionally defocused to an approximate radius of about 3 arcsec, equivalent to  $\sim 12$  physical pixels, to avoid saturation and to minimize systematic errors due to pixel inhomogeneities and imperfect flat-field correction. The exposure time ranged between 2 to 6 s, depending on the weather conditions and the amount of defocus applied. For each observation, an out-of-transit part was secured about one hour before ingress and one hour after egress for normalization and detrending purposes. Bias and flat-field frames were collected following the standard data reduction techniques. We carried out a preliminary selection of our frames, checking for any quality issues (e. g., pixels exceeding the saturation level, strong cosmic-ray hits, etc.). After identifying the problematic frames, we removed the corresponding data points from each light curve. In 6 of the 28 observations, clouds, high humidity, veils, and other weather conditions prevented a full complete transit from being observed. We did not exclude from our analysis the partial transits when at least the ingress or the egress were well sampled, since most of the timing information lies at those phases where the time derivative of the flux is larger.

Table 2.1: Observing log of our unpublished transit light curves of WASP-12b.

| ID | Evening date | Telescope | $N$  | Filter    | Exptime [s] | RMS [mmag] | Phase coverage         |
|----|--------------|-----------|------|-----------|-------------|------------|------------------------|
| 1  | 2010-12-11   | 1.82-m    | 2996 | $R_C$     | 4-5         | 3.46       | Full transit           |
| 2  | 2010-12-12   | 1.82-m    | 2366 | $R_C$     | 4-5-7       | 4.55       | Full transit           |
| 3  | 2011-02-06   | Schmidt   | 1223 | $R_C$     | 10          | 4.11       | Full transit           |
| 4  | 2011-11-22   | 1.82-m    | 494  | $R_C$     | 10          | 1.96       | Full transit           |
| 5  | 2011-11-23   | 1.82-m    | 2393 | $R_C$     | 5           | 1.81       | Full transit           |
| 6  | 2011-12-17   | 1.82-m    | 1881 | $R_C$     | 4-7         | 3.20       | Full transit           |
| 7  | 2011-12-27   | 1.82-m    | 3077 | $R_C$     | 4           | 2.95       | Full transit           |
| 8  | 2011-12-28   | 1.82-m    | 2456 | $R_C$     | 5           | 2.32       | Full transit           |
| 9  | 2012-02-24   | 1.82-m    | 2449 | $R_C$     | 5           | 2.84       | Full transit           |
| 10 | 2012-10-21   | 1.82-m    | 1881 | $R_C$     | 5           | 2.55       | Partial (egress only)  |
| 11 | 2012-12-19   | 1.82-m    | 2268 | $R_C$     | 5           | 1.75       | Full transit           |
| 12 | 2013-01-11   | 1.82-m    | 2287 | $R_C$     | 4-5-7       | 2.48       | Full transit           |
| 13 | 2013-02-04   | 1.82-m    | 2509 | $R_C$     | 5           | 2.50       | Full transit           |
| 14 | 2013-12-02   | 1.82-m    | 2784 | $R_C$     | 4           | 2.77       | Partial (only ingress) |
| 15 | 2014-03-05   | 1.82-m    | 1945 | $R_C$     | 4           | 4.13       | Partial (only ingress) |
| 16 | 2015-12-11   | 1.82-m    | 2680 | SDSS $r'$ | 3           | 2.81       | Partial (only egress)  |
| 17 | 2015-12-12   | 1.82-m    | 3204 | SDSS $r'$ | 2           | 2.68       | Full transit           |
| 18 | 2017-01-20   | 1.82-m    | 2646 | SDSS $r'$ | 3           | 3.01       | Full transit           |
| 19 | 2017-12-20   | 1.82-m    | 2084 | SDSS $r'$ | 5           | 2.56       | Full transit           |
| 20 | 2018-01-12   | 1.82-m    | 2437 | SDSS $r'$ | 4           | 2.90       | Full transit           |
| 21 | 2019-12-29   | 1.82-m    | 2376 | SDSS $r'$ | 5           | 1.70       | Full transit           |
| 22 | 2020-01-22   | 1.82-m    | 3080 | SDSS $r'$ | 4           | 2.29       | Full transit           |
| 23 | 2020-11-06   | 1.82-m    | 4045 | SDSS $r'$ | 2           | 3.87       | Full transit           |
| 24 | 2020-11-17   | 1.82-m    | 2942 | SDSS $r'$ | 4           | 2.69       | Full transit           |
| 25 | 2021-10-29   | 1.82-m    | 2419 | SDSS $r'$ | 5           | 3.23       | Full transit           |
| 26 | 2021-12-28   | 1.82-m    | 1805 | SDSS $r'$ | 4           | 3.51       | Partial (egress only)  |
| 27 | 2022-01-08   | 1.82-m    | 1350 | SDSS $r'$ | 4-5         | 2.56       | Partial (ingress only) |
| 28 | 2022-03-08   | 1.82-m    | 2845 | SDSS $r'$ | 4           | 2.73       | Full transit           |

The columns show: a numerical identifier, the evening date of the observation, the telescope used, the number  $N$  of valid scientific frames acquired during the observation, the photometric filter, the average exposure time in seconds, the RMS of the residuals and the approximate phase coverage.

### 2.2.2 Spectroscopy

WASP-12 was observed with HARPS-N at TNG at a spectral resolution of 110 000, in the framework of the GAPS project (Covino et al. 2013). A total of 51 HARPS-N spectra, taken from November 2012 to January 2018, were used in this study. An analysis including the first 15 spectra was published by Bonomo et al. (2017) together with the result of the other 44 stars observed in that study. Additionally, we used eight spectra from the same program, which are still unpublished. The main purposes of these first 23 observations were to refine the planetary parameters and to search for additional companions through high-precision RV monitoring (individual RV errors ranging from 2 to 10 m/s). The remaining 28 spectra were obtained during planetary transits and adjacent off-transit windows on the nights 2017 December 23 and 2018 January 14 as part of the GAPS program to study the planetary atmospheres of hot Jupiters (Guilluy et al. 2022). The individual spectra were reduced with the standard Data Reduction Software version 3.8. A coadded spectrum was then created using all the spectra, achieving a mean S/N of  $\sim 220$  at around  $6000 \text{ \AA}$ . The HARPS-N spectra described above were exploited in this paper to characterize the host star (see Sect. 2.3.3). For WASP-12, there are no indications of additional companions, and the updated RV analysis yielded a RV semi-amplitude of  $219.90 \pm 2.2 \text{ m/s}$ , corresponding to a planetary mass of  $1.39 \pm 0.12 M_{\text{Jup}}$ , with no significant eccentricity ( $e < 0.02$ ).

## 2.3 Data analysis

### 2.3.1 Light curve extraction

After the images underwent bias and flat field correction, we performed differential aperture photometry and extracted the light curves by employing the STARSKY photometric pipeline, originally designed for the TASTE project (Nascimbeni et al. 2011; Nascimbeni et al. 2013), and based entirely on an empirical approach. This pipeline performs aperture photometry on the target and a set of reference stars, and combines their fluxes to get high-precision differential light curves, where instrumental or telluric systematic errors are mitigated. The error bars on each data point were calculated with the analytic formulae quoted by Nascimbeni et al. (2011) (Eqs. 1 and 2) and through standard statistical propagation.

The aperture radius was set to include most of the flux of the target and the reference stars, and to minimize the off-transit scatter of each light curve. The optimal radius fell in the range of 9-23 pixels. For consistency, all observations utilized the same set of two reference stars as indicated in Sect. 2.2.1 for consistency. Before the extraction, all the light curves were detrended with a linear function of time at the extraction stage, as part of the STARSKY standard processing (Nascimbeni et al. 2011; Nascimbeni et al. 2013).

In order to represent all our time stamps to a single, accurate time standard, we translated them to the mid-exposure instant and converted them to the BJD-TDB standard, following the prescription by Eastman et al. (2010). It is worth mentioning the light curve ID=23 is the only one in our set that shows an unexpected feature, a 5 mmag deep, 6 min long dip right after the end of ingress (see Fig. 2.5). Although the overall RMS of this light curve is higher than average due to a high background level (bright moon at  $\sim 20^\circ$ ), there

is no clear correlation between the feature and any of our diagnostic parameters, including guiding drifts, stellar FWHM, transparency, background. The dip is independent of the choice of reference stars, and is even visible in the absolute light curve. We conclude that the feature is probably genuine, and due to the crossing of an active region during the transit. We come back to this explanation in Sect. 2.4.4.

### 2.3.2 Light curve modeling

We analyzed the whole set of 28 transit light curves simultaneously using the package PyORBIT<sup>1</sup> (Malavolta et al. 2016; 2018) developed for modeling planetary transits and radial velocities. In the fitting procedure, the central time of transit  $T_0$  was left free to vary for every transit. As each data set includes a single transit, a uniform prior on each central time of transit  $T_0$  is automatically generated by taking as boundaries the first and last epoch of the corresponding data set. In those cases where only a partial light curve was observed and the  $T_0$  falls outside the observed window (namely, ID# 10, 14, 15, 16, 27), the uniform prior was set manually via visual inspection.

We imposed a Gaussian prior on the orbital period ( $P$ ) and the stellar radius, based on the values from Bonomo et al. (2017). We adopted a quadratic law to model WASP-12's limb darkening (LD) effect, employing the limb darkening parameterization ( $q_1, q_2$ ) introduced by Kipping (2013). The limb darkening coefficients are associated with two sets of Gaussian priors, one for each filter, centered on the prediction of the PHOENIX atmospheric models (Husser et al. 2013) with an added conservative uncertainty of 0.10.

We assumed a circular orbit. The effect of nonzero eccentricity on the light curve implies a difference in the ingress and egress times. This difference is  $10^{-2} \times e$  for a close-in planet (Winn 2010). Since our eccentricity is  $\leq 0.02$  (see Sect. 2.3.3) the effect on the light curve is negligible. Additionally, for a short-period planet orbiting a star as old as WASP-12 (see Table 2.5), we can consider that the orbit is circularized (Nagasawa et al. 2008, Fig. 4).

For each data set, we included a jitter term to account for possible underestimation of measurement errors and short-term stellar activity white noise. We also used a quadratic baseline (three extra free parameters for each light curve) for transits ID# 3, 4, 5, 14, 15, 21, and 22, (i.e., for those where the corresponding BIC value indicated a significant improvement in fit as a result of the inclusion of the detrending baseline). Finally, because no contaminants fall inside the photometric aperture adopted, the dilution factor is negligible, and is not included in the fit.

The free parameters in the fit accounted for: 3 parameters for the transit shape, 4 for the LD parameters, 28 for the transit times, 28 for the jitter and 15 ( $3 \times 5$ ) for the detrending parameters. This amounts to a total of 78 free parameters.

All the transit models were computed with the popular package *batman* (Kreidberg et al. 2015), with an exposure time of 5 s and an oversampling factor of 1. The differential evolution algorithm PyDE<sup>2</sup> was used to conduct global parameter optimization. The output parameters served as the starting point for the Bayesian analysis, which was carried out using the *emcee* (Foreman-Mackey et al. 2013) package, a Markov chain Monte Carlo algorithm. We ran an auto-correlation analysis on the chains: if the chains were longer

<sup>1</sup><https://github.com/LucaMalavolta/PyORBIT>

<sup>2</sup><https://github.com/hpparvi/PyDE>

than 100 times the estimated auto-correlation time and this estimate varied by less than 1%, the chains were deemed converged. We cautiously set the burn-in value to a number greater than the previously stated convergence point, and we used a precautionary value of 1000 for the thinning factor. We ran the sampler for 75 000 steps, with 680 walkers and a burn-in cut of 25 000 steps. Table 2.2 shows all the 28 transit central times obtained from the PyORBIT fit. The resulting best-fit parameters and the priors are shown in Table 2.3. The light curves and the corresponding PyORBIT best-fitting models are plotted in Figs. 2.3-2.6.

### 2.3.3 Stellar parameters

The coadded spectrum was analyzed as in Biazzo et al. (2022) to derive the effective temperature  $T_{\text{eff}}$ , the surface gravity  $\log g$ , the microturbulence velocity  $\xi$ , the iron abundance  $[\text{Fe}/\text{H}]$ , and the rotational velocity  $v \sin i_{\star}$  of WASP-12. For  $T_{\text{eff}}$ ,  $\log g$ ,  $\xi$ , and  $[\text{Fe}/\text{H}]$  we applied a method based on equivalent widths (EWs) of 81 Fe I and 11 Fe II lines taken from Biazzo et al. (2015) and Biazzo et al. (2022) and the spectral analysis package MOOG (Snedden 1973; version 2017). We then adopted the Castelli & Kurucz (2003a) grid of model atmospheres with solar-scaled chemical composition and new opacities. The parameters  $T_{\text{eff}}$  and  $\xi$  were derived by imposing that the abundance of the Fe I lines is not dependent on the line excitation potentials and the reduced equivalent widths (i.e.  $EW/\lambda$ ), respectively, while  $\log g$  was obtained by imposing the ionization equilibrium condition between the abundances of Fe I and Fe II lines.

The  $v \sin i_{\star}$  was measured with the same MOOG code and applying the spectral synthesis technique of three regions around 5400, 6200 and 6700 Å. We adopted the grid of model atmosphere mentioned above and, after fixing the macroturbulence velocity to the value of 5.5 km/s from the relationship by Doyle et al. (2014), we find an upper limit for the stellar  $v \sin i_{\star}$  of 1.9 km/s.

From the same coadded spectrum, we also derived the abundance of the lithium line at  $\sim 6707.8$  Å  $\log A(\text{Li})$ , after measuring the Li EW ( $39.5 \pm 1.5$  Å) and considering our stellar parameters previously derived together with the non-LTE corrections by Lind et al. (2009). We therefore obtained  $2.55 \pm 0.05$  dex as NLTE lithium abundance. Lithium equivalent width and elemental abundance values for a star with an effective temperature like that of WASP-12 are intermediate between those of clusters of 2 Gyr, such as NGC752, and  $\sim 4$  Gyr, such as M67 (Sestito & Randich 2005; Jeffries et al. 2023). The final atmospheric stellar parameters, together with iron and lithium elemental abundances are listed in Table 2.4, where uncertainties were computed as in Biazzo et al. (2022).

In order to determine the mass, radius, density and age, we followed the same approach as described in Sect. 3.2 of Lacedelli et al. (2021). We used the code ISOCHRONES (Morton 2015), with posterior sampling through the code MULTINEST (Feroz & Hobson 2008; Feroz et al. 2009, 2019). We provided as input the photometry from the Two Micron All Sky Survey 2MASS, WISE, and the parallax of the target from the Gaia Early Data release(eDR3) (see Table 2.5 for the adopted stellar parameters). The analysis was performed using two evolutionary stellar models, the MESA Isochrones & Stellar Tracks (MIST) (Dotter 2016; Choi et al. 2016; Paxton et al. 2011) and the Dartmouth Stellar Evolution Database (Dotter et al. 2008).

We derived from the mean and standard deviation of all posterior samplings,  $M_{\star} =$

Table 2.2: New best-fit transit times of WASP-12b.

| ID | $T_0$ (BJD-TDB) | $\sigma_{T0}$ [days] |
|----|-----------------|----------------------|
| 1  | 2455542.553168  | 0.000189             |
| 2  | 2455543.643326  | 0.000297             |
| 3  | 2455599.307161  | 0.000540             |
| 4  | 2455888.533480  | 0.000180             |
| 5  | 2455889.624786  | 0.000135             |
| 6  | 2455913.635896  | 0.000204             |
| 7  | 2455923.458691  | 0.000164             |
| 8  | 2455924.549735  | 0.000125             |
| 9  | 2455982.395378  | 0.000160             |
| 10 | 2456222.508576  | 0.000210             |
| 11 | 2456281.444317  | 0.000103             |
| 12 | 2456304.364434  | 0.000133             |
| 13 | 2456328.375176  | 0.000143             |
| 14 | 2456629.607692  | 0.000266             |
| 15 | 2456722.377750  | 0.000272             |
| 16 | 2457368.498222  | 0.000225             |
| 17 | 2457369.589776  | 0.000125             |
| 18 | 2457774.507194  | 0.000156             |
| 19 | 2458108.480490  | 0.000148             |
| 20 | 2458131.399324  | 0.000171             |
| 21 | 2458847.370515  | 0.000186             |
| 22 | 2458871.381793  | 0.000155             |
| 23 | 2459160.606724  | 0.000164             |
| 24 | 2459171.521679  | 0.000132             |
| 25 | 2459517.500786  | 0.000194             |
| 26 | 2459577.528473  | 0.000253             |
| 27 | 2459588.443252  | 0.000175             |
| 28 | 2459647.379007  | 0.000128             |

The numerical IDs match those assigned on Table 2.1. The transit times are given in the BJD-TDB standard (Eastman et al. 2010); the third column reports the associated 1- $\sigma$  error.

$1.325^{+0.026}_{-0.018} M_{\odot}$ ,  $R_{\star} = 1.690^{+0.019}_{-0.018} R_{\odot}$ . The stellar density  $\rho_{\star} = 0.27 \pm 0.010 \rho_{\odot}$  was derived directly from the posterior distributions of  $M_{\star}$  and  $R_{\star}$ . These stellar parameters, together with the age, are listed in Table 2.4.



Table 2.3: WASP-12b orbital parameters derived from PyORBIT Markov chain Monte Carlo analysis.

| Parameter                                           | Units     | Prior                                 | Posterior value                         |
|-----------------------------------------------------|-----------|---------------------------------------|-----------------------------------------|
| FITTED PARAMETERS                                   |           |                                       |                                         |
| Orbital Period ( $P$ )                              | [days]    | $\mathcal{U}[1.09142090, 0.00000020]$ | $1.0914210^{+0.00000019}_{-0.00000020}$ |
| Impact Parameter ( $b$ )                            | –         | $\mathcal{U}[0, 1 + (R_\star/R_p)/2]$ | $0.424^{+0.012}_{-0.013}$               |
| Quadratic Limb Darkening term $c_1$ ( $R_C$ filter) | –         | $\mathcal{U}[0.412, 0.10]$            | $0.349^{+0.029}_{-0.029}$               |
| Quadratic Limb Darkening term $c_2$ ( $R_C$ filter) | –         | $\mathcal{U}[0.148, 0.10]$            | $0.167^{+0.049}_{-0.049}$               |
| Quadratic Limb Darkening term $c_1$ (SDSS.r filter) | –         | $\mathcal{U}[0.428, 0.10]$            | $0.369^{+0.030}_{-0.031}$               |
| Quadratic Limb Darkening term $c_2$ (SDSS.r filter) | –         | $\mathcal{U}[0.15, 0.10]$             | $0.109^{+0.053}_{-0.051}$               |
| DERIVED PARAMETERS                                  |           |                                       |                                         |
| Semimajor axis ( $a$ )                              | [au]      | –                                     | $0.0234^{+0.0010}_{-0.0010}$            |
| Inclination ( $i$ )                                 | [deg]     | –                                     | $81.80^{+0.29}_{-0.27}$                 |
| Planet Radius ( $R_p$ )                             | [ $R_J$ ] | –                                     | $1.965^{+0.088}_{-0.087}$               |
| Transit duration ( $T_{14}$ )                       | [days]    | –                                     | $0.12504 \pm 0.00018$                   |

The listed best-fit values and uncertainties are the medians and 15.865th-84.135th percentiles of the posterior distributions, respectively.

### 2.3.4 Timing analysis

We searched for the shrinking of the orbital period to constrain the orbital decay effects. Similar to Patra et al. (2020), Yee et al. (2019) and Turner et al. (2021) we implement two models to fit the timing data. The first is the linear ephemeris model, which assumes that the orbital period is constant:

$$T_{\text{lin}} = T_0 + P \times E \quad (2.1)$$

Here  $E$ ,  $T_0$  and  $P$  are respectively the transit epoch, the reference mid-transit time (corresponding to  $E = 0$ ) and the orbital period. The second model is quadratic, and assumes that the orbital period is varying uniformly over time:

$$T_{\text{quad}} = T_0 + P \times E + \frac{1}{2} \frac{dP}{dE} \times E^2 \quad (2.2)$$

Here  $dP/dE$  is the change in the orbital period between consecutive transits, which is assumed constant. The best-fitting model parameters were found by performing a DEMCMC analysis (100 000 steps with 1000 burn-in steps) of all the timings in Tab. 2.2. We adopted as the new zeroth epoch the transit time closest to the average of the available timings, to minimize the correlation between the ephemeris parameters, as done for instance by Dragomir et al. (2011) and Mallonn et al. (2019). The results of the quadratic model are:

$$T_0 = 2457280.093510 \pm 0.000067 \quad (\text{BJD-TDB}), \quad (2.3)$$

$$P = 1.0914192185 \pm 0.000000041 \quad \text{days}, \quad (2.4)$$

$$\frac{dP}{dE} = (-1.063 \pm 0.093) \times 10^{-9} \quad \text{days/orbit}, \quad (2.5)$$

$$\frac{dP}{dt} = -30.72 \pm 2.67 \quad \text{ms/yr}. \quad (2.6)$$

Table 2.4: Stellar parameters of WASP-12 derived from the analysis of the HARPS-N spectra and from stellar evolutionary tracks.

| Parameter                                | Value                     |
|------------------------------------------|---------------------------|
| $T_{\text{eff}}$ [K]                     | $6265 \pm 50$             |
| $\log g$ [cgs]                           | $4.11 \pm 0.11$           |
| [Fe/H] [dex]                             | $0.12 \pm 0.07$           |
| $\xi$ [km s <sup>-1</sup> ]              | $1.39 \pm 0.08$           |
| $v \sin i_{\star}$ [km s <sup>-1</sup> ] | $< 1.9$                   |
| $EW_{\text{Li}}$ [mÅ]                    | $39.5 \pm 1.5$            |
| $\log A(\text{Li})$ [dex]                | $2.55 \pm 0.05$           |
| $A_V$ [mag]                              | $0.321 \pm 0.096$         |
| $M_{\star}$ [ $M_{\odot}$ ]              | $1.325^{+0.026}_{-0.018}$ |
| $R_{\star}$ [ $R_{\odot}$ ]              | $1.690^{+0.019}_{-0.018}$ |
| $\rho_{\star}$ [ $\rho_{\odot}$ ]        | $0.274 \pm 0.010$         |
| Age [Gyr]                                | $3.05 \pm 0.32$           |

The corresponding  $O - C$  (observed minus calculated) diagram is shown in Fig. 2.1 as a function of the epoch  $E$ . The derivative of the orbital period  $dP/dE$  is derived from the quadratic coefficient of the best-fitting parabola in Eq. 2.2, and then translated into  $dP/dt$ . Its negative sign indicates a decrease in the orbital period with a rate of 0.03071 seconds per year. The corresponding orbital decay timescale would be  $\tau = -(dP/dt)/P = 3.07 \pm 0.26$  Myr, a value consistent with the results of Turner et al. (2021) and Wong et al. (2022) (see Table 2.6).

To further test the orbital decay hypothesis, we combine our homogeneous ground-based data set with all the available mid-transit times (356) compiled by Bai et al. 2022. The data encompass timings from ground-based facilities as well as TESS results and data by amateur astronomers collected by ETD (Poddaný et al. 2010). All the literature timings and the filters used are listed in the additional tables at CDS. The resulting parameters of the quadratic fit, performed as in the former case, are:

$$T_0 = 2457607.519305 \pm 0.000032 \quad (\text{BJD-TDB}), \quad (2.7)$$

$$P = 1.091418901 \pm 0.000000018 \quad \text{days}, \quad (2.8)$$

$$\frac{dP}{dE} = (-1.082 \pm 0.042) \times 10^{-9} \quad \text{days/orbit}, \quad (2.9)$$

$$\frac{dP}{dt} = -31.27 \pm 1.23 \quad \text{ms/yr}. \quad (2.10)$$

We used these parameters to compute the  $O - C$  diagram shown in Fig. 2.2. We note that the planetary parameters reported in Table 2.3 were derived based on the Asiago photometry alone, and are therefore independent from any literature work.

As already shown by several previous studies (Patra et al. 2017; Yee et al. 2019; Turner et al. 2021) the quadratic model provides a much better fit with respect to the linear

Table 2.5: Astrophysical properties of WASP-12

| Parameter                            | Value               | Reference |
|--------------------------------------|---------------------|-----------|
| <i>Identifiers</i>                   |                     |           |
| 2MASS                                | J06303279+2940202   | 1         |
| Gaia DR3                             | 3435282862461427072 | 2         |
| <i>Astrometric Parameters</i>        |                     |           |
| RA [J2000]                           | 06:27:21.28         | 2         |
| Dec [J2000]                          | 29:42:26.84         | 2         |
| Parallax [mas]                       | $2.4213 \pm 0.0166$ | 2         |
| $\mu_\alpha$ [mas yr <sup>-1</sup> ] | $-1.518 \pm 0.019$  | 2         |
| $\mu_\delta$ [mas yr <sup>-1</sup> ] | $-6.760 \pm 0.015$  | 2         |
| <i>Photometric parameters</i>        |                     |           |
| B[mag]                               | $12.14 \pm 0.21$    | 3         |
| V[mag]                               | $11.57 \pm 0.16$    | 3         |
| J[mag]                               | $10.477 \pm 0.021$  | 1         |
| H[mag]                               | $10.228 \pm 0.022$  | 1         |
| K[mag]                               | $10.188 \pm 0.020$  | 1         |
| W1[mag]                              | $10.111 \pm 0.022$  | 4         |
| W2[mag]                              | $10.109 \pm 0.021$  | 4         |
| W3[mag]                              | $10.121 \pm 0.073$  | 4         |

- (1) Two Micron All Sky Survey (2MASS; Cutri et al. 2003; Skrutskie et al. 2006);  
(2) Gaia eDR3 (Gaia Collaboration 2020)  
(3) Tycho-2 Catalogue (Høg et al. 2000)  
(4) Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010)

ephemeris. This is also confirmed in our goodness-of-fit statistic, by the quadratic model (25 degrees of freedom, d.o.f) chi-square ( $\chi^2$ ) 770.87 against the linear model (26 d.o.f) value of 2463.66 and by the Bayesian information criterion (BIC; Schwarz 1978). The orbital decay model is favored with a value of  $\Delta(\text{BIC}) = 1693$  against the linear model.

## 2.4 Discussion

### 2.4.1 Tidal orbital decay

The measured fast rate of orbital decay for WASP-12b has been attributed to tidal dissipation inside its host star. A short-period planetary system experiences a tidal orbital decay if the host star rotates more slowly than the orbital period of the planet. In this scenario, the orbital angular momentum of the planet is transferred to the spin of the star because the tidal bulge lags behind the position of the planet in its orbit. The orbital energy of the planet, deposited in the tidal bulge within the host star, is dissipated by tides, which causes the star to spin up (Zahn 1977; Hut 1981; Eggleton et al. 1998). The transfer of angular momentum from the planetary orbit to the stellar spin causes the orbital separation

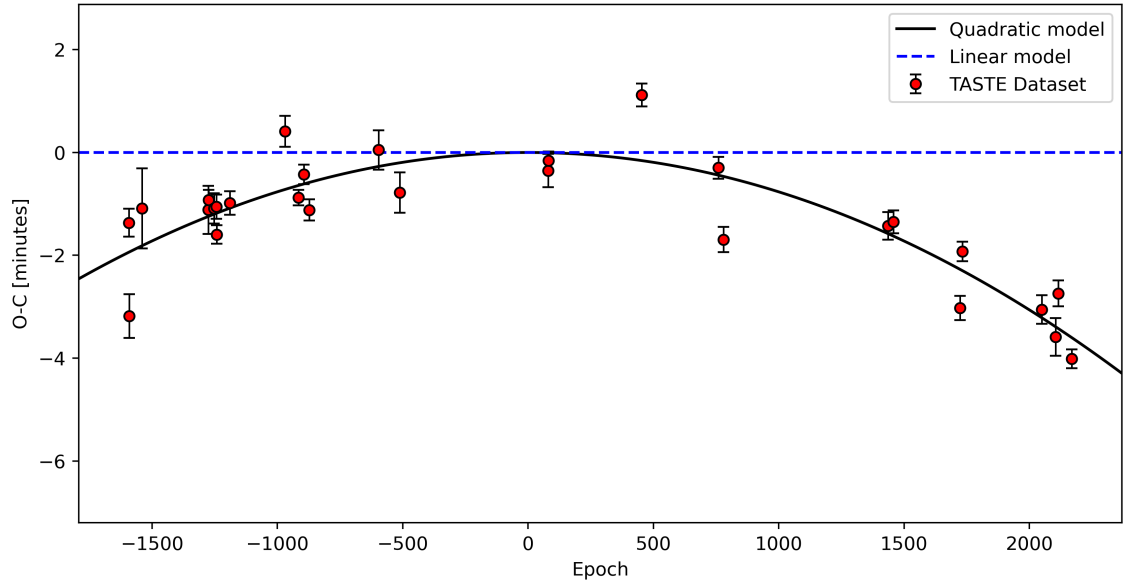


Figure 2.1: Observed minus calculated ( $O - C$ ) diagram of WASP-12b for the unpublished transits collected at Asiago (Tables 2.1 and 2.2). The reference ephemeris here is the linear part of Eq. 2.3, while the additional quadratic term (based on  $dP/dE$ ) is plotted as a black solid line. An excess scatter in the data points with respect to the quadratic model can be seen in the figure. This is addressed in Sect. 2.4.4.

between the planet and the host star to shrink (along with orbital circularization) leading ultimately to the engulfment of the planet after the stellar Roche radius limit is reached (Levrard et al. 2009). Orbital decay in a close-in, short-period exoplanet can be detected via long-monitoring transit-timing variations observational campaigns (Miralda-Escudé 2002; Agol et al. 2005; Holman & Murray 2005).

## 2.4.2 Stellar tidal quality factor

The tidal quality factor  $Q$  is defined as the ratio of the total energy of the tide to the total energy dissipated in one tidal period (see, e.g. Eq. 2.19 of Zahn 2008). When dealing with tidal dissipation, we pair  $Q$  with the Love number  $k_2$ , which takes into account the internal density stratification of the object. Directly measuring the decrease in the orbital period can be used to estimate the modified stellar tidal quality factor  $Q'_* \equiv 3Q_*/2k_2$  (Matsumura et al. 2010; Hoyer et al. 2016; Penev et al. 2018; Turner et al. 2022). This dimensionless parameter measures the efficiency of the dissipation of the kinetic energy of the tides inside the star. We can deduce its value using the constant-phase-lag (CPL) model of Goldreich & Soter (1966):

$$Q'_* = -\frac{27}{2}\pi \left(\frac{M_p}{M_*}\right) \left(\frac{a}{R_*}\right)^{-5} \left(\frac{dP}{dt}\right)^{-1} \quad (2.11)$$

where  $M_p/M_*$  is the planet-to-star mass ratio,  $R_*$  is the stellar radius,  $a$  is the semimajor axis and  $dP/dt$  is the period derivative. By taking our derived values of  $M_*$ ,  $dP/dt$ ,  $R_*$ ,  $a$ , see Sects. 2.3.3 and 2.3.4, and the planetary mass of Chakrabarty & Sengupta (2019),

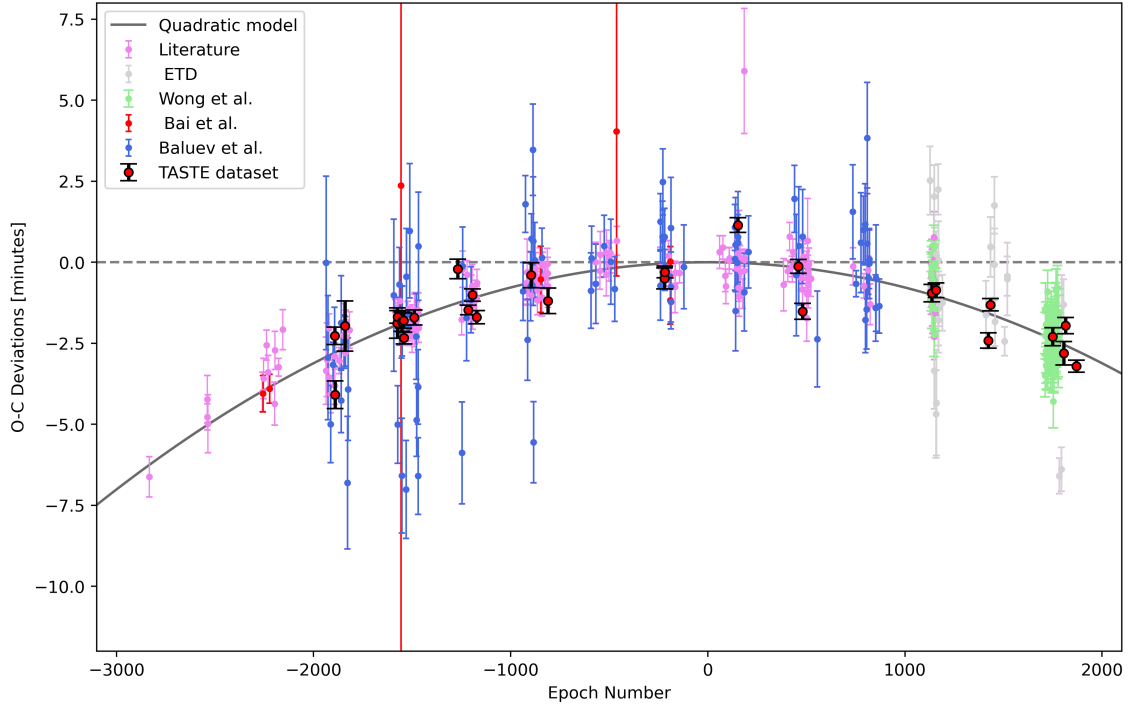


Figure 2.2: Observed minus calculated ( $O - C$ ) diagram of WASP-12b for all the available transit-timing data. The reference ephemeris here is the linear part of Eq. 2.7, while the additional quadratic term (based on  $dP/dE$ ) is plotted as a black solid line. The Asiago data are plotted as black and red points, the remaining points come from the literature: Bai et al. (2022) (red, including TESS), Wong et al. (2022) (light green), Baluev et al. (2019) (light blue), other literature works (available at CDS, pink). Amateur timings from ETD are plotted in gray.

we obtained a modified tidal quality factor of

$$Q'_* = (2.13 \pm 0.18) \times 10^5. \quad (2.12)$$

The planetary mass is assumed to be constant, which we know from Lai et al. (2010) not to be the case. This value is slightly higher, but still consistent, compared to what is derived by Turner et al. (2021) and Wong et al. (2022).

In the literature, there is a substantial disagreement between the value of  $Q'_*$  determined from the WASP-12 studies and the observed or theoretically predicted ranges of values. Our derived value is at the lower limit of the observed ranges as derived from population studies of hot Jupiters ( $10^{5.5}$ - $10^{6.5}$ ; Jackson et al. 2008; Husnoo et al. 2012; Bonomo et al. 2017; Barker 2020) and binary star systems ( $10^5$ - $10^7$ ; Meibom & Mathieu 2005; Ogilvie & Lin 2007; Lanza et al. 2011; Meibom et al. 2015). Collier Cameron & Jardine (2018) used a form of Bayesian hierarchical inference to numerically estimate the modified stellar quality factor for hot Jupiters. Their analysis found mean values of  $Q'_* \sim 10^{7.3}$  and  $10^{8.3}$ , for the dynamical and equilibrium tide regimes, respectively. The authors expected a departure from a linear ephemeris for WASP-12b of less than 1 s, on a 20 yr baseline. We can see from Fig.2.1 and Fig.2.2 that our observations greatly exceed that prediction showing a variation of minutes on a 12 yr baseline. Hamer & Schlaufman (2019) and

Barker (2020) argued that the findings of population-wide studies of hot Jupiters should be taken as approximate estimates considering that the value of  $Q'_*$  depends on the physical and mechanical properties (orbital period, stellar interior structure and rotation period, planet and stellar mass) of the individual star-planet systems. In this regard, Rosário et al. (2022) studied WASP-18b, a massive hot Jupiter ( $\sim 11 M_J$ ) on a 0.94 day period orbiting a star with a spectral type and mass similar to those of WASP-12, finding however a lower limit for the tidal quality factor of two orders of magnitude higher than that of WASP-12b.

Furthermore, based on the current understanding of tidal dissipation processes, the physical mechanism driving this efficient dissipation inside WASP-12 is yet to be understood. The tide in the star is frequently divided into two components: an equilibrium tide and a dynamical tide (Zahn 1977). The damping of the equilibrium tide in the convective layers is too weak to explain the observed strong dissipation. Linear and nonlinear wave-breaking of the dynamical tide ( $g$ -modes) near the radiative core of the star would lead to a sufficiently enhanced dissipation ( $Q'_* \sim 10^5$ ) only if the star has entered its subgiant stage of evolution (Weinberg et al. 2017).

The presence and size of the radiative core, which can be derived from the internal structure of the star, is fundamental to understanding the tidal decay mechanism. If WASP-12 were still on the main sequence, it would possess a convective envelope and a small convective core. However, if it had evolved to become a subgiant it would hold a radiative core, allowing gravity waves to deposit their angular momentum at the radiative-convective boundaries by breaking, resulting in a fast tidal decay (Weinberg et al. 2017; Weinberg et al. 2023). However, our precise observational constraints on the stellar parameters, such as mass, effective temperature, age and metallicity, are consistent with the main-sequence structure if compared to the theoretical models of Weinberg et al. (2017) and Bailey & Goodman (2018). In order to further investigate the evolutionary phase of WASP-12 we used the MESA Isochrone & Stellar Tracks (MIST) stellar evolution models, to extract the theoretical isochrone equivalent to our derived value of  $[\text{Fe}/\text{H}]$  and stellar age (see Tab. 2.4). We placed the star in the  $\log(T_{\text{eff}})$ - $\log(L/L_{\odot})$  diagram (H-R diagram), plotted in Fig. 2.7, where the isochrone is displayed as a solid black line. The star is located in an ambiguous position, between the main sequence and the turn-off, but far away from the subgiant branch. This could tell us, as suggested by Efroimsky & Makarov (2022), that the star has entered the post-turn-off stage where hydrogen fusion in the core has ceased, ultimately leading to the core contraction and the burning of hydrogen in a shell around the core.

Recent studies proposed alternative hypotheses in which the observed tidal orbital decay can be explained by obliquity tides (Millholland & Laughlin 2018), planetary eccentricity tides (Efroimsky & Makarov 2022), or a spin-orbit coupling mediated by a non-axisymmetric gravitational quadrupole moment inside the planet (Lanza 2020). Although significant improvements have been made in our observations of the system, there is still a need for more precise modeling to address the numerous unresolved questions and test both stellar evolution and tidal theories. Asteroseismology is a promising approach to determine whether WASP-12 is a main-sequence or a subgiant star by measuring the age of the star, the mixing length parameter  $\alpha$ , the size of the convective core or the presence of a core rotation, as suggested by previous studies (Deheuvels et al. 2016; Weinberg et al. 2017; Bailey & Goodman 2018; Fellay et al. 2023).

### 2.4.3 The search for orbital decay in other systems

Among the population of hot Jupiters, WASP-12b is the first case where orbital decay was detected. Several studies over the years investigated the decaying orbit of hot Jupiters, which possess orbital features similar to the target of our study (Patra et al. 2020; Ivshina & Winn 2022; Hagey et al. 2022).

Harre et al. (2023) used CHEOPS and TESS high-precision photometric data to investigate the orbital decay of WASP-4 b, KELT-9 b and KELT-16 b. In agreement with Turner et al. (2022) and Bouma et al. (2019), they found a changing orbit only for WASP-4b, but even if the orbital decay model is preferred, apsidal precession cannot be ruled out with the available data. Additional transit and occultations are needed to clearly identify the cause of the period variation.

Vissapragada et al. (2022) presented strong evidence for the tidal decay of Kepler-1658 b, a close-in giant planet orbiting a subgiant star, using a 13-year observational baseline. Using RVs, the authors ruled out apsidal precession on theoretical grounds and line-of-sight acceleration. The computed value of the modified tidal quality factors ( $Q'_* = 2.50^{+0.85}_{-0.62} \times 10^4$ ) fully agrees with what should result from the dissipation of inertial waves in the convective zone. The recently discovered hot Jupiter TOI-2109b (Wong et al. 2021) presents orbital and stellar characteristics that could lead to a stronger tidal dissipation than WASP-12b. Additional new observations with a long observational baseline are needed to detect a potential orbital decay.

According to the expected tidal decay rates and host star properties, many other planets should exhibit significant rates of orbital decay, for example WASP-18b (Collier Cameron & Jardine 2018), WASP-19b (Rosário et al. 2022), WASP-43b (Patra et al. 2020), WASP-103b (Barros et al. 2022), WASP-161b (Yang & Chary 2022), KELT-16b (Harre et al. 2023) and HATS-18b (Southworth et al. 2022). To date, not enough evidence has been found from the available data to confirm a decaying orbit for any of these systems. Several effects can produce an  $O - C$  variation over a long baseline; thus, to have a successful validation of a planet tidal orbital inspiral and discard any other different possible cause a decade-long observational baseline, is necessary. Many of these targets will be reobserved by TESS, CHEOPS, PLATO (Nascimbeni et al. 2022) and Ariel (Borsato et al. 2022) in the near future and could be used in a future collective study. However, as advocated by Hamer & Schlaufman (2019), we additionally suggest that the focus of orbital decay studies should also be on planets orbiting host stars at the end of their main-sequence lifetimes.

### 2.4.4 Excess scatter in the timing data

An evident feature of our data is the presence of excess scatter in the  $O - C$  plot (Fig. 2.1): the reduced  $\chi^2$  of the fit on the Asiago data set is  $\chi^2_r = 5.52$  ( $\chi^2 \sim 138$  for 25 d.o.f), implying that the error bars are about  $\sim 2.3$  times too small with respect to a well-behaved Gaussian distribution having the same variance. This cannot be attributed to issues in the absolute calibration of our time stamps, or to systematic errors left uncorrected by our photometric pipeline, as other TASTE studies carried out with the same setup and data analysis technique demonstrated a timing accuracy at the 1 s level or better (Brown-Sevilla et al. 2021). Such an excess is not unique to our unpublished data set. The best fit to the overall  $O - C$  diagram (Fig. 2.2) yields  $\chi^2_r \sim 2$ , and other independent data sets reach a

value of  $\chi_r^2$  significantly larger than one (e. g.,  $\chi_r^2 \sim 2.1$  for Baluev et al. 2019 and  $\chi_r^2 \sim 8$  for ETD).

We investigated the impact of correlated noise on our results by analyzing the residuals of our light curve (i.e. after the best-fit transit model is subtracted). This was done by calculating the  $\beta$  factor after binning the time series on different time scales (Gillon et al. 2006; Winn et al. 2007a). When correlated noise is present, the binned rms  $\sigma$  is larger by a factor of  $\beta$  with respect to the ideal white-noise case, where the rms is supposed to decrease by the square root of the number of points per bin ( $\sqrt{N}$ ). On the timescale corresponding to the ingress-egress duration ( $\sim 23$  min for WASP-12b), which is the most relevant timescale for the transit-time estimation,  $\beta$  usually lies in the 1.5-2 range for well-behaved ground-based photometry (Winn et al. 2007b). Among our 28 light curves, only four of them (#2, 7, 20, 28) show an unusually large amount of red noise ( $\beta \gg 2$ ), but #20 is the only one that is also a significant outlier in the  $O - C$  diagram.

As a further check, we binned each complete light curve on the timescale of the ingress duration (0.0159 days), then re-performed the global fitting process on complete transits in the same way as explained in Sect. 2.3.2. The resulting  $\chi_r^2$  is 3.2 ( $\chi^2 = 64.8$  with 20 d. o.f.) which is, still considerably larger than one. Even though the error bars increased, the sign of the most significant outliers is unchanged. We also note that our best-fit  $dP/dt$  in the binned case is  $-29 \pm 4$  msec/year, fully in agreement with the previous value of  $-30.7 \pm 2.7$  msec/year obtained without binning the light curves (Eq. 2.3).

These exercises demonstrate that, while a few light curves show a higher-than-usual amount of correlated noise, there is no obvious link with the excess scatter we found in the measured transit times. We also note that the presence of partial transits in our data set cannot explain this excess: the reduced  $\chi^2$  for just our 22 complete transits is  $\chi_r^2 = 5.78$  ( $\chi^2 = 110$  for 19 d. o. f.), almost identical to the  $\chi_r^2 = 5.52$  value for the full distribution ( $\chi^2 = 137$  for 25 d. o. f.).

It is well known in the literature that comparing timing data extracted from ground-based transit light curves can be prone to systematic errors due to a combination of telluric and/or instrumental red noise and different reduction techniques (Baluev et al. 2019). On the other hand, excess scatter is sometimes noticed also when dealing with space-based data (as in Turner et al. 2022; Harre et al. 2023 in the case of WASP-4), and it is usually attributed to the presence of stellar activity. Little is known about the stellar activity properties of WASP-12b; its anomalously low  $R_{HK}$  value could be due to the presence of extra absorption from escaped circumstellar gas (Fossati et al. 2010) and no coherent rotational modulation can be detected from its light curve. However, significant bumps are visible in the residuals of the TESS data (Wong et al. 2022), and at least one of our light curves (#23) shows an in-transit anomaly which is difficult to explain with systematic errors (Sect. 2.3), suggesting that in some cases inhomogeneities may arise on the stellar photosphere of WASP-12 but do not result in a detectable rotational modulation because of the high inclination of the stellar axis with respect to the observer, also suggested by the unusually low  $v \sin i$ . If the pole-on hypothesis is true, the timing scatter we see could be the only observable hint so far that WASP-12 is actually a significantly active star.

Intriguingly, even though running a GLS periodogram on our  $O - C$  residuals does not result in any significant frequency, the excess scatter appears to be a time-dependent phenomenon. Transits gathered during some observing seasons (such as 2011-2012 and 2019-2020) line up within seconds of the average quadratic ephemeris and return  $\chi_r^2 \sim 1$



even on the Asiago subset, while others (such as 2020-2021) appear much more scattered on different and independent data sets.

Forthcoming additional photometry from TESS (scheduled on two sectors –71 and 72– in November-March 2023) will possibly shed some more light on this behaviour. Meanwhile, we emphasize that, despite the scatter excess, our homogeneous data set, published here for the first time, represents a fully independent confirmation of the tidal decay process in WASP-12b, at an estimated rate perfectly consistent with those derived by previous studies.

## 2.5 Summary and conclusions

In this work we inspected the tidal orbital decay of the ultra-hot Jupiter WASP-12b, using 28 unpublished, high-precision, ground-based light curves collected over 12 years, from 2010 to 2022, as part of the TASTE program. We applied a DE-MCMC approach, for a linear (constant period) and quadratic model (orbital decay), to the timing of our homogeneously collected observations confirming the decaying orbit of WASP-12b.

Our new planetary and transit parameters are in good agreement with previous studies. However, combining all the timing data from literature we found some discrepancies in the  $O - C$  plot. The timing data shows an excess of scatter that cannot be attributed to errors in the photometric pipeline or the calibration of the time stamps. This raises several questions that will require further study to resolve.

We used HARPS-N observations to investigate the evolutionary stage of the host star, which is fundamental to explain the high rate of tidal dissipation. The applied spectroscopic observations allowed us to derive precise stellar parameters of the host star, however, we did not arrive at a firm conclusion regarding the evolutionary stage. The stellar parameters enable us to place the star in the main sequence close to the turn-off point and away from the subgiant branch. However, the fast tidal dissipation requires a subgiant scenario.

Table 2.6: Comparison of the values of period change rate and orbital decay timescale of WASP-12b as estimated by different literature works.

| Reference           | Period change rate $dP/dt$<br>[ms/year] | Orbital decay timescale $P / (dP/dt)$<br>[Myr] |
|---------------------|-----------------------------------------|------------------------------------------------|
| This work           | $-30.71 \pm 2.67$                       | $3.07 \pm 0.26$                                |
| Patra et al. 2017   | $-29 \pm 3$                             | $3.2 \pm 0.38^\dagger$                         |
| Yee et al. 2019     | $-29 \pm 2$                             | $3.25 \pm 0.24$                                |
| Turner et al. 2021  | $-32.53 \pm 1.6$                        | $2.90 \pm 0.14$                                |
| Ivshina & Winn 2022 | $-32.53 \pm 1.62$                       | $3.11 \pm 0.11^\dagger$                        |
| Wong et al. 2022    | $-29.81 \pm 0.94$                       | $3.16 \pm 0.10$                                |
| Bai et al. 2022     | $-37.14 \pm 1.31$                       | $2.54 \pm 0.09$                                |

$^\dagger$  value calculated by us, missing in the original paper.

## 2.6 Appendix: Additional Plots

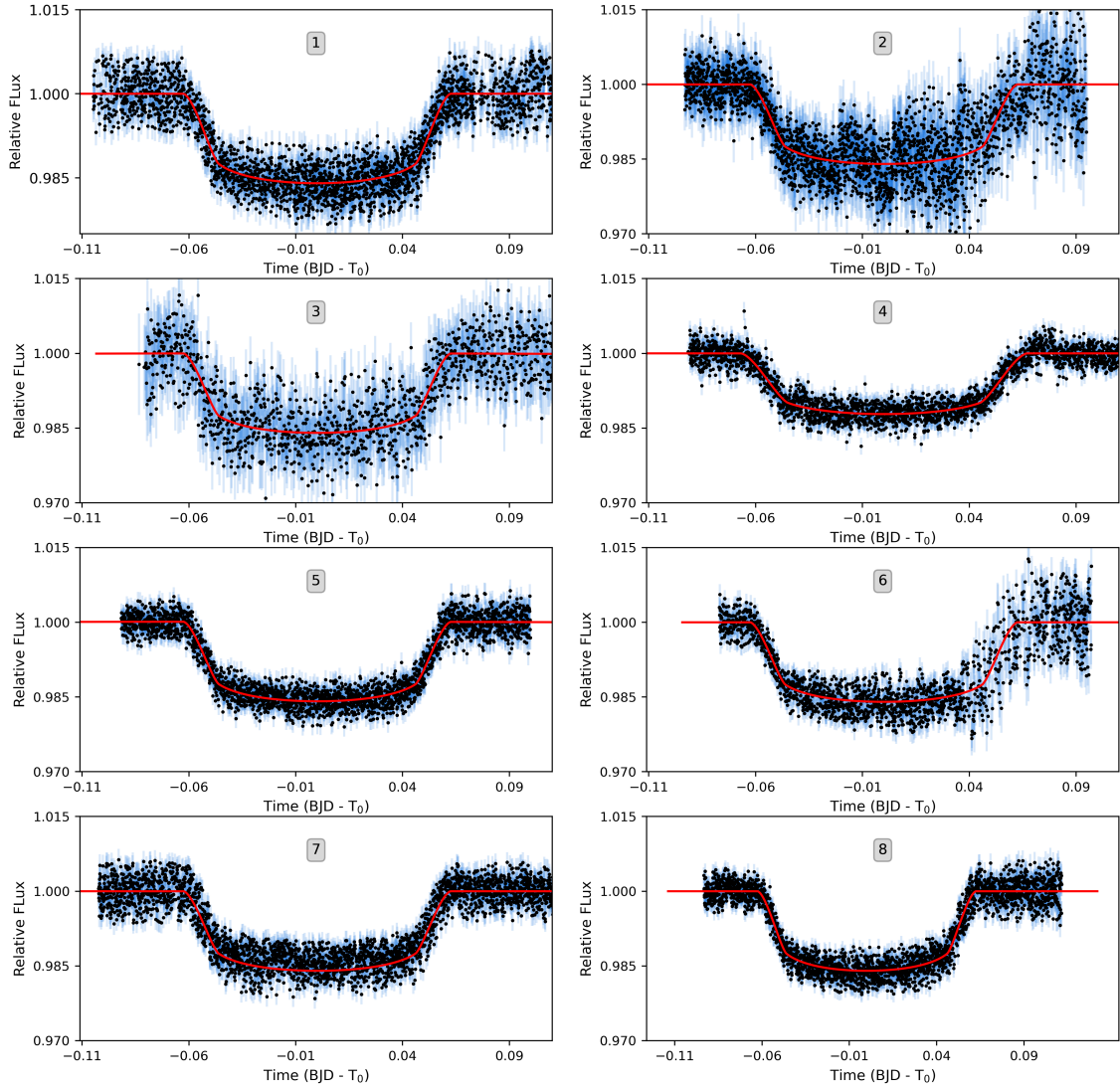


Figure 2.3: Individual TASTE transits light curves of WASP-12 b. The best-fitting PyORBIT model (obtained in Sect. 2.3.2) is shown as a red line. The ID for each transit is shown in the center of each panel.

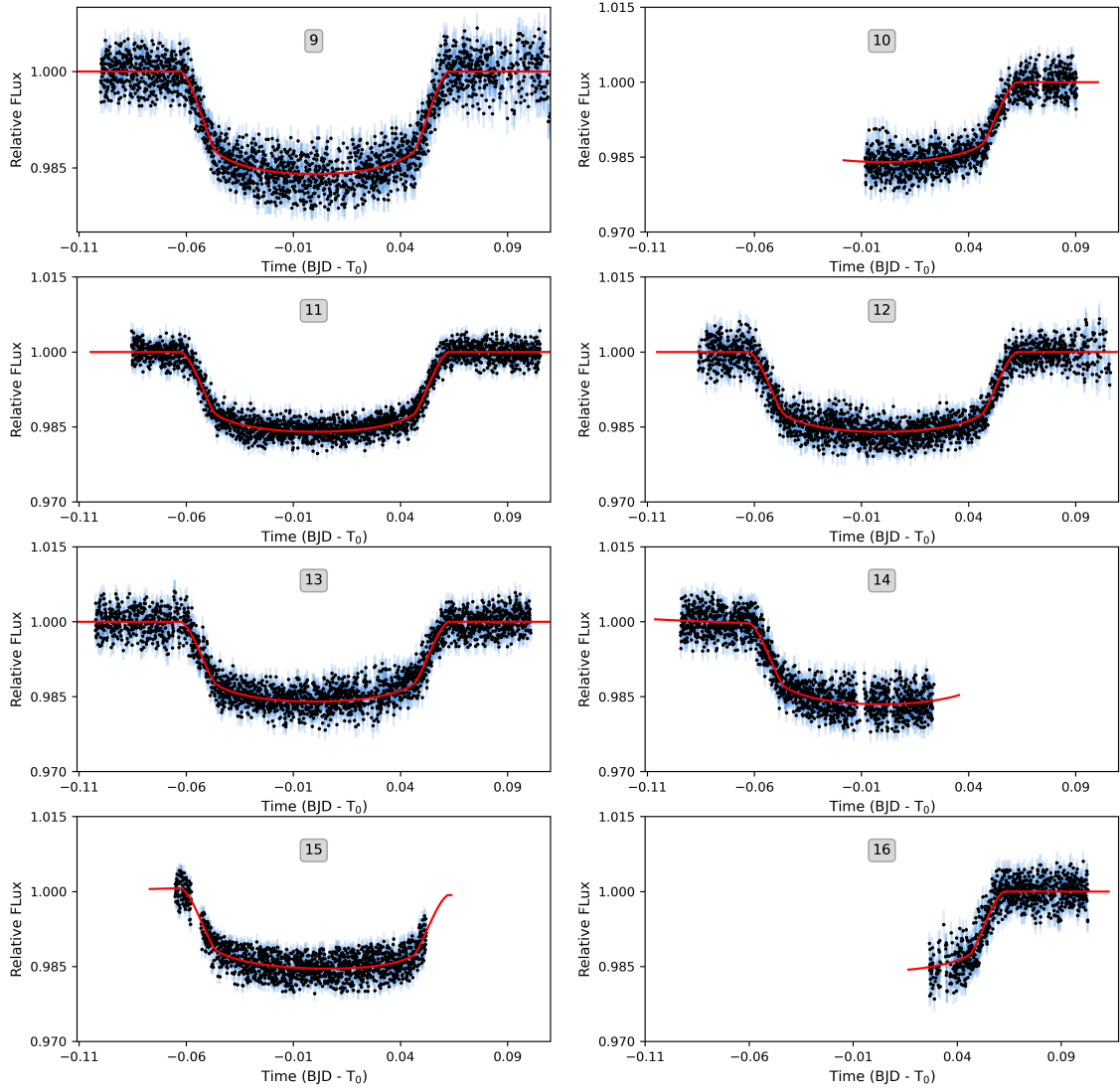


Figure 2.4: Same as Figure 2.3 but for observations 9 through 16.

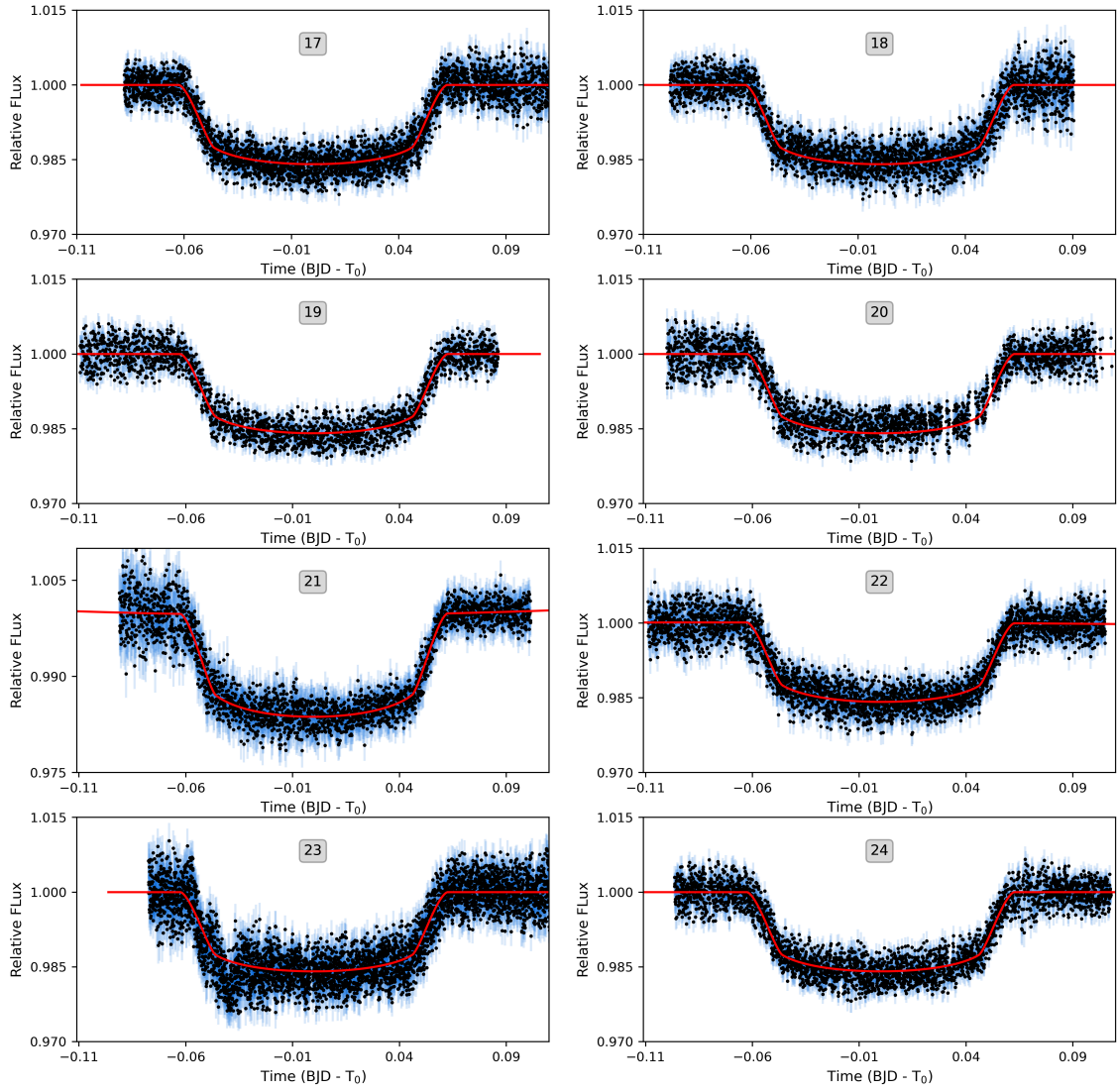


Figure 2.5: Same as Figure 2.3 but for observations 17 through 24.

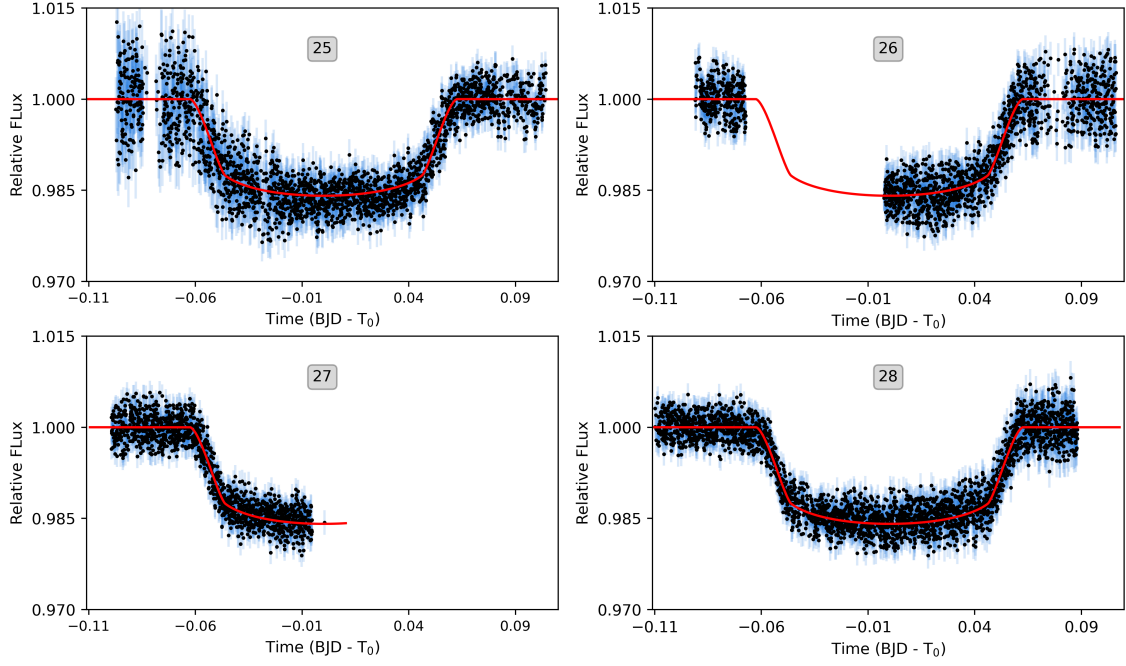


Figure 2.6: Same as Figure 2.3 but for observations 25 through 28.

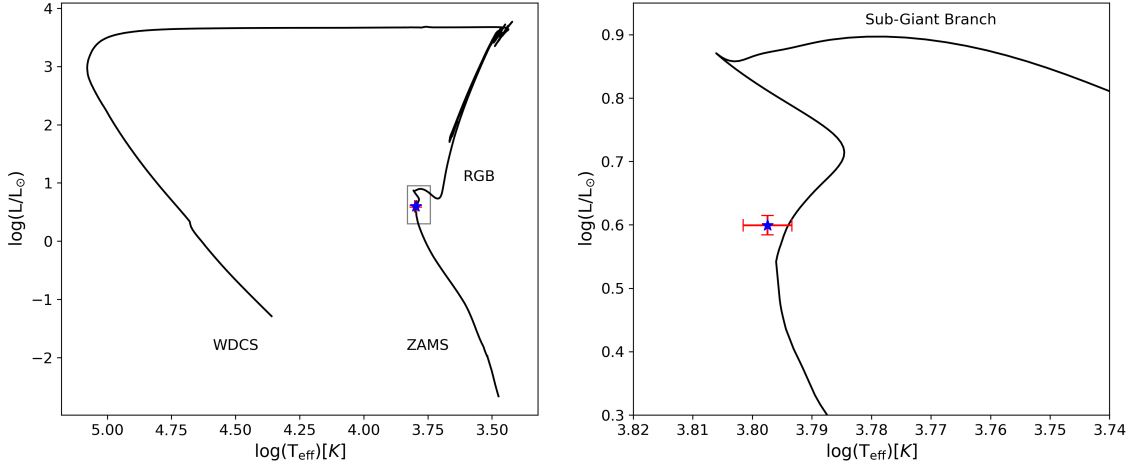


Figure 2.7: H-R diagram displaying the effective temperature  $T_{eff}$  versus luminosity  $L/L_{\odot}$ , the isochrone from the MESA Isochrone & Stellar Tracks (MIST) stellar evolution models is shown as a solid black line. The location of WASP-12 is shown with a filled blue star. The gray box marks the zoomed-in region shown in the right panel. Right: zoomed in view of the diagram.



# 3

## Transit Timing Variations in HIP 41378: CHEOPS and TESS confirm a non-transiting sixth planet in the system

**Foreword:** In multiple-planet systems, gravitational interactions of exoplanets could lead to transit timing variations (TTVs), whose amplitude becomes significantly enhanced when planets are in or near mean-motion resonances (MMRs), making them more easily detectable. In cases where both TTVs and radial velocity (RV) measurements are available, combined analysis can break degeneracies and provide robust planetary and system characterization, even detecting non-transiting planets. In this context, HIP 41378 hosts five confirmed transiting planets with periods ranging from 15 to over 542 days, providing a unique dynamical laboratory for investigating wide multi-planet systems analogous to the Solar System. In this study, we present an intensive space-based photometric follow-up of HIP 41378, combining 15 new CHEOPS observations with eight TESS sectors, alongside data from K2, Spitzer, HST, and 311 HARPS spectra. We dynamically modeled the TTVs and RV signals of the two inner sub-Neptunes via N-body integration. These planets, HIP 41378 b ( $P_b = 15.57$  days,  $R_b = 2.45 R_\oplus$ ) and HIP 41378 c ( $P_c = 31.71$  days,  $R_c = 2.57 R_\oplus$ ), are close to ( $\Delta \sim 1.8\%$ ) a 2:1 period commensurability. We report a clear detection of TTVs with amplitudes of 20 minutes for planet b and greater than 3 hours for planet c. We dynamically confirm the planetary nature of HIP 41378 g, a non-transiting planet with a period of about 64 days and a mass of about  $7 M_\oplus$ , close to a 2:1 commensurability with planet c, suggesting a possible mean-motion resonance chain in the inner system. Our precise determination of the masses, eccentricities, and radii of HIP 41378 b and c enabled us to investigate their possible volatile-rich compositions. Finally, by leveraging on the last TESS sectors we constrained the period of HIP 41378 d to three possible aliases ( $P_d = 278, 371$ , and 1113 days) suggesting that the system could be placed in a

double quasi resonant chain, highlighting its complex dynamical architecture.

Based on:

Leonardi P., et al. 2025, *Astronomy and Astrophysics*, Accepted: 11 September 2025, <https://doi.org/10.1051/0004-6361/202555253>

### 3.1 Introduction

Following the conclusion of the primary *Kepler* mission, NASA’s *K2* mission expanded the search for transiting exoplanets by targeting stars along the ecliptic plane (Howell et al. 2014). Unlike *Kepler*, which focused on a fixed field, *K2* covered a broader sky region, observed a more diverse stellar population, and prioritized brighter stars, making them ideal candidates for radial-velocity (RV) follow-up studies. These extensive long-term surveys led to the unexpected discovery of numerous sub-Neptune-sized planets ( $1.75 R_{\oplus} \lesssim R_p \lesssim 3.5 R_{\oplus}$ , following Kopparapu et al. 2018) in compact, coplanar multi-planetary systems (e.g., Borucki et al. 2011; Latham et al. 2011; Weiss et al. 2018; Bean et al. 2021). The prevalence of such systems has made them key cornerstones of exoplanet research, offering crucial insights into planetary formation and evolution while bridging the gap between the Solar System and the wide diversity of known exoplanetary architectures (Bean et al. 2021). Among this population, sub-Neptunes on long-period orbits are exceptionally valuable. Situated at larger orbital distances, they are shielded from the intense stellar X-ray and ultraviolet (XUV) radiation that drives atmospheric escape via photoevaporation (Lopez & Fortney 2014; Owen & Wu 2017). Consequently, these planets are expected to retain their primordial atmospheres. Their present-day atmospheric properties, such as mass fraction and composition, therefore, offer a more direct probe of the conditions within the proto-planetary disk during their formation as well as their evolution. This makes them prime targets for constraining planet formation models through atmospheric characterization studies (Madhusudhan 2019; Bean et al. 2021). In this context, the multi-planet system around the bright ( $m_V = 8.93$ ) late F-type star HIP 41378 (K2-93) stands out as one of only five systems, alongside those around 55 Cnc (Butler et al. 1997), HD 219134 (Gillon et al. 2017), HD 110067 (Luque et al. 2023), HD 191939 (Badenas-Agusti et al. 2020), and Kepler-444 (Campante et al. 2015) that host more than four confirmed planets with both mass and radius constraints, while also hosting a star brighter than  $m_V = 9$  mag.

The system was first identified by Vanderburg et al. (2016) during Campaign 5 of the *K2* mission (April–July 2015). After its discovery, the system was reobserved three years later during Campaign 18 (May–July 2018) (Berardo et al. 2019, hereafter B19; Becker et al. 2019). The *K2* data revealed a system of five transiting planets (from b to f), with the two inner sub-Neptunes (HIP 41378 b and c) exhibiting well-constrained orbital periods of 15.6 and 31.7 days respectively, near a 2:1 period commensurability. However, for the three outer planets, an insufficient number of transits were recovered to determine their orbital periods, leaving only a set of possible period aliases. Based on the 75-day baseline of the *K2* C5 campaign and the long transit durations of the planets, the highest-probability aliases derived suggested long-period orbits for the outer planets ( $P > 100$  days). The first mass measurements of the planets in the system were obtained



by Santerne et al. (2019, hereafter S19) using radial velocity (RV) observations from HARPS, HARPS-N, the Carnegie Planet Finder Spectrograph (PFS; Crane et al. 2006, 2008, 2010) and HIRES (High Resolution Echelle Spectrometer). The authors detected strong RV signals from planets b, c, and f, but were unable to retrieve any signal from planets d and e. Additionally, they identified a periodic signal at  $\sim 62$  days, attributed to a possible non-transiting planet (hereafter HIP 41378 g) near a 2:1 period commensurability with planet c raising the possibility of strong dynamical interactions among the inner three planets in a near-resonant chain, which could result in observable transit timing variations (TTVs) (Agol et al. 2005; Holman & Murray 2005). Their analysis also constrained the orbital period of HIP 41378 f to  $P_f = 542$  days, making it one of the longest-period planets discovered via transit photometry. A subsequent intensive ground-based follow-up by Bryant et al. (2021) confirmed this period and revealed significant TTVs, indicating strong dynamical interactions among the outer planets.

In this work, we present a global dynamical analysis of the sub-Neptunes HIP 41378 b and HIP 41378 c. This combines 15 single-visit observations from the *CHaracterising ExOPlanets Satellite* (CHEOPS; Benz et al. 2021), eight new sectors from the *Transiting Exoplanet Survey Satellite* (TESS; Ricker et al. 2015), archival photometry from *Kepler* (K2), *Spitzer*, and the Hubble Space Telescope (HST), and RV measurements from HARPS (Mayor et al. 2003). Using measurements from *Spitzer*, B19 reports hints of TTV for planet c, with variations exceeding one hour. Motivated by this detection, we analyzed the potential TTVs of HIP 41378 c and HIP 41378 b. Additionally, we examined the dynamical influence of the non-transiting candidate planet HIP 41378 g, assessing its role in shaping the observed TTVs and the overall dynamics of the system. The paper is organized as follows: In Sect. 3.2, we describe the spectroscopic and photometric observations. Section 3.3 presents the newly derived stellar parameters. Section 3.4 details the photometric and dynamical modeling, including transit timing extraction and orbital parameter retrieval. Our results are presented in Section 3.5. In Section 3.6, we discuss the system’s architecture, the implications of the inner planets’ ”peas-in-a-pod” configuration, and potential planetary compositions. The possible atmospheric evolutions and their future characterization are described in Section 3.6.5 and 3.6.6. Lastly, Section 3.7 summarizes the key findings and outlines future observational priorities.

## 3.2 Observations extraction and reduction

This section presents the observations and data extraction of both proprietary CHEOPS light curves and publicly available spectroscopic and photometric data for HIP 41378 b & c (including K2, TESS, *Spitzer*, HST, and HARPS), spanning over 10 years and comprising a total of 47 transit light curves (32 for -b and 15 for -c). For each TESS sector and K2 campaign, we isolated individual transits of both planets by selecting portions of the light curve that encompassed the transit duration plus three CHEOPS orbits ( $\sim 98.77$  minutes each). This allowed us to have a consistent out-of-transit baseline across all observations. The center of the transits, determined using a linear ephemeris, and the transit durations were based on the values reported by B19.

### 3.2.1 K2

The *K2* mission observed the system during campaign 5 (2015 April 27 – 2015 July 10) and campaign 18 (2018 May 12 – 2018 July 02), under the identifier EPIC 211311380 (K2-93), with long- and short-cadence photometry (30-minutes and 1-minute, respectively). A total of 10 transits of planets b & c were observed during the *K2* mission (seven of b and three of c). From the Mikulski Archive for Space Telescopes (MAST<sup>1</sup>) we extracted the high-level science data products (HLSP) based on the photometric pipeline EVEREST (EPIC Variability Extraction and Removal for Exoplanet Science Targets, version 2.0; Luger et al. 2016, 2018).

### 3.2.2 Spitzer

We used photometric data of HIP 41378 collected with the Infrared Array Camera (IRAC) 4.5  $\mu\text{m}$  channel of *Spitzer* telescope (Werner et al. 2004), taken as part of the observing programs 11026 and 13052 (PI: Werner), focused on *K2* follow-ups. The observations, presented by B19, cover a transit of planet b and one of planet c.

### 3.2.3 TESS

The *TESS* mission Ricker et al. (2015) observed the system (TOI-4304, TIC 366443426) from Cycles 1 to 7 in sectors: 7, 34, 44, 45, 46, 61, 72 and 88 with a cadence of 120 s. We downloaded the photometric time series processed by the Science Processing Operations Center (SPOC; Jenkins et al. 2016) from the MAST archive, and we corrected the Simple Aperture Photometry (SAP) for systematic effects by following the procedure and using the Cotrending Basis Vectors described in Nardiello et al. (2021, 2025). As shown in Nardiello et al. (2022), Pre-search Data Conditioned SAP (PDC-SAP) light curves can suffer of over-correction problems, that can introduce new systematic errors in the light curves and change the shape of the stellar activity and planetary transits, and also mimic false transit signals. A total of nine transits of planet b and six of planet c were extracted from the light curves. The first transit of planet b during sector 72 fell in a data discontinuity gap, thus only a partial transit light curve was retrieved.

### 3.2.4 HST

We used the publicly available HST/WFC3 (Marinelli & Green 2024) transit observations of HIP 41378 b from the MAST archive. These data, obtained using the G141 grism (1.088 to 1.680  $\mu\text{m}$ ), cover three transits of the planet (2018-01-14, 2018-05-03 and 2020-05-20) and were taken as part of program GO-15333 (PI: Ian Crossfield). The data was first published by Edwards et al. (2023a), and later re-analyzed by Brande et al. (2024). Each of the three visits covers seven HST orbits, with a total exposure time of 138.38 s (scan rate of 0.25 s<sup>-1</sup>) and eight up-the-ramp samples per exposure. For wavelength calibration purposes we used, at the beginning of each orbit, a direct image captured with the F126N filter. The first orbit was not included in our analysis because it contained large time-dependent systematic errors. Both the forward and reverse scanning direction were

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<sup>1</sup><https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>

used for these observations. The calibration of the raw WFC3 data, the reduction and the extraction of the white light curves were done using the IRACIS dedicated pipeline (Tsiaras et al. 2016a,b, 2018), following the methodology of Edwards et al. (2023a). Our reduction also includes the frame-splitting method (see Edwards et al. 2023b, for a complete description) that takes into account the persistence effect dependent upon the brightness of the host star, the scanning rate, and the readout scheme employed. The extracted HST/WFC3 light curves present significant time-dependent systematics, including a linear long-term (“visit ramps”) and exponential short-term (“orbit ramps”) trend. We modeled these slopes together with a scaling factor between upstream and downstream spatial scans using Eq. 1 of Edwards et al. (2023a).

### 3.2.5 CHEOPS

HIP 41378 was observed with CHEOPS within the frame of the Guaranteed Time Observation (GTO) as part of two programs: M-R relation in planetary systems<sup>2</sup>, dedicated to TTVs follow-up of planetary systems to better constrain masses, orbital parameters, and planetary compositions (Nascimbeni et al. 2023, 2024), and Architecture of Resonant Chains (ARC)<sup>3</sup>, centered on the TTV follow-up of resonant chains (Leleu et al. 2021; Delrez et al. 2023; Leleu et al. 2024). We obtained 15 visits acquired between 2020-12-23 and 2025-03-11, of which 11 were centered on transits of planet b and four on those of planet c. For each observation we used the exposure cadence of 38 seconds, avoiding saturation. The complete log of the observations is reported in Tab. 3.2. The CHEOPS raw data were automatically processed by the CHEOPS Data Reduction Pipeline (DRP v13.1.0; Hoyer et al. 2020). The DRP corrects for instrumental (e.g bias, flat and dark current) and environmental effects (e.g cosmic rays, background) (Fortier et al. 2024). The pipeline performs aperture photometry extracting four different light-curves. For our study we used the light-curve corresponding to the DEFAULT photometric aperture of 25 pixels, which has the lowest rms. Following the extraction of the light curves we performed a clipping of the outliers with respect to the median flux value of the light curves plus five times the mean absolute deviation (MAD).

### 3.2.6 HARPS

We recovered the publicly available HARPS (Mayor et al. 2003) high-precision RV observations from the ESO Science Archive website<sup>4</sup>. We downloaded 370 spectra obtained under the observing programs 198.C-0169(A) and 0102.C-0171(A) (PI: Santerne) previously published by Santerne et al. (2019). The system was monitored between January 2017 and April 2019, with a typical integration time of 15 minutes. The observations yielded a median formal measurement uncertainties of  $2 \text{ m s}^{-1}$ . The spectra were extracted using the HARPS online data reduction pipeline (DRS) (Cosentino et al. 2014, version 3.8). We rejected the points taken to monitor granulation and p-modes in the two consecutive nights: 2018-03-10 and 2018-03-11. We additionally discarded all the data

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<sup>2</sup>CH.PR100025, V. Nascimbeni

<sup>3</sup>CH.PR140080, A. Leleu

<sup>4</sup>[http://archive.eso.org/wdb/wdb/adp/phase3\\_main/form](http://archive.eso.org/wdb/wdb/adp/phase3_main/form)

Table 3.1: Derived stellar parameters of HIP 41378.

| Parameter                          | Value                     |
|------------------------------------|---------------------------|
| $T_{\text{eff}}$ [K]               | $6371 \pm 65$             |
| $\log g$ [cgs]                     | $4.32 \pm 0.02$           |
| [Fe/H] [dex]                       | $0.046 \pm 0.044$         |
| $v \sin i_{\star}$ [km s $^{-1}$ ] | $7.5 \pm 0.5$             |
| $M_{\star}$ [ $M_{\odot}$ ]        | $1.245^{+0.037}_{-0.043}$ |
| $R_{\star}$ [ $R_{\odot}$ ]        | $1.306 \pm 0.010$         |
| $\rho_{\star}$ [ $\rho_{\odot}$ ]  | $0.557 \pm 0.016$         |
| Age [Gyr]                          | $1.8^{+0.7}_{-0.6}$       |
| [Mg/H] [dex]                       | $0.04 \pm 0.07$           |
| [Si/H] [dex]                       | $0.04 \pm 0.04$           |

points with an error greater than  $5\sigma$  of the median value. These selections left us with 311 RV measurements.

### 3.3 Stellar parameters

The stellar spectroscopic parameters ( $T_{\text{eff}}$ ,  $\log g$ , microturbulence  $v_{\text{tur}}$ , and [Fe/H]) were derived using the ARES+MOOG methodology as described in Santos et al. (2013); Sousa (2014); Sousa et al. (2021). For this we used the latest version of ARES<sup>5</sup> (Sousa et al. 2007, 2015) to consistently measure the equivalent widths (EW) of selected iron lines in the combined HARPS spectrum of HIP 41378. For this, we used the iron line list presented in Sousa et al. (2008). The best spectroscopic parameters are found by converging into ionization and excitation equilibrium. In this process, a grid of Kurucz model atmospheres (Kurucz 1993) and the radiative transfer code MOOG (Snedden 1973) are used. We also derived a more accurate trigonometric surface gravity using the *Gaia* DR3 data following the same procedure as described in Sousa et al. (2021). Stellar abundances of Si and Mg were then derived using the classical curve-of-growth analysis method assuming local thermodynamic equilibrium. The same codes and models were used for abundance determinations. For the derivation of chemical abundances of refractory elements, we closely followed the methods described in (e.g., Adibekyan et al. 2012, 2015). All of the [X/H] ratios were obtained by performing a differential analysis with respect to a high S/N solar (Vesta) spectrum from HARPS. We determined the HIP 41378 stellar radius using a Markov chain Monte Carlo (MCMC) modified infrared flux method (IRFM – Blackwell & Shallis 1977; Schanche et al. 2020). Within this MCMC framework, we produced synthetic photometry from a constructed spectral energy distribution (SED) based on stellar atmosphere models (Castelli & Kurucz 2003b), using our spectroscopically derived stellar parameters as priors. To compute the stellar bolometric flux, we compared these simulated data to broadband fluxes in the following bandpasses: 2MASS  $J$ ,  $H$ , and  $K$ ,

<sup>5</sup>The latest version, ARES v2, can be downloaded at <https://github.com/sousasag/ARES>

WISE  $W1$  and  $W2$ , and *Gaia*  $G$ ,  $G_{BP}$ , and  $G_{RP}$  (Skrutskie et al. 2006; Wright et al. 2010; Gaia Collaboration et al. 2022). Lastly, this was converted into the effective temperature and angular diameter, from which we derived the stellar radius via combination with the offset-corrected *Gaia* parallax (Lindgren et al. 2021). Assuming  $T_{\text{eff}}$ ,  $[\text{Fe}/\text{H}]$ , and  $R_{\star}$  along with their uncertainties as input parameters, we derived the isochronal mass and age using two different stellar evolutionary models. The first set of mass and age estimates was computed using the isochrone placement routine (Bonfanti et al. 2015, 2016), which interpolates the input parameters within precomputed grids of PARSEC<sup>6</sup> v1.2S (Marigo et al. 2017) isochrones and evolutionary tracks. The second set of mass and age values, instead, was estimated via the CLES (Code Liègeois d’Évolution Stellaire; Scuflaire et al. 2008) code, which builds up the best-fit evolutionary track following a Levenberg-Marquadt minimization scheme (see, e.g., Salmon et al. 2021). After checking the mutual consistency of the two respective pairs of outcomes via the  $\chi^2$  criterion outlined in Bonfanti et al. (2021), we finally computed our final estimates for the mass and age that turned out to be  $M_{\star} = 1.245^{+0.037}_{-0.043} M_{\odot}$  and  $t_{\star} = 1.8^{+0.7}_{-0.6}$  Gyr; see Bonfanti et al. (2021) for further details about the statistical treatment. The stellar parameters are summarized in Tab. 3.1. Our derived stellar parameters were found to be consistent with asteroseismic values from Lund et al. (2019). Given the higher precision offered by asteroseismology, we adopted the asteroseismic constraints from Lund et al. (2019) as priors for all our subsequent analysis.

## 3.4 Data Analysis

In this section, we describe the photometric and dynamical modeling to retrieve the planetary parameters.

### 3.4.1 CHEOPS-only analysis

Upon visually examining the CHEOPS data, each light curve presented significant systematics. We used the PyORBIT<sup>7</sup> software (Malavolta et al. 2016, 2018) to simultaneously fit a transit model and detrend each individual CHEOPS light curve. All visits corresponding to the same planet were modeled using a common transit model. A set of 14 instrumental and environmental detrending vectors<sup>8</sup> was applied globally across all light curves. These included: spacecraft roll-angle( $\phi$ ) ( $df/d \cos \phi$ ,  $df/d \sin \phi$ ,  $df/d \cos 2\phi$ ,  $df/d \sin 2\phi$ ,  $df/d \cos 3\phi$ ,  $df/d \sin 3\phi$ ), background level ( $df/dbg$ ), photometric contamination estimate ( $df/dcontam$ ), smear estimate ( $df/dsmear$ ), thermal variation  $\Delta T$  of CHEOPS sensors, x centroid and y centroid ( $df/dx$ ,  $d^2f/dx^2$ ,  $df/dy$ ,  $d^2f/dy^2$ ). The detrended transit light curves, were then used for the global fitting.

### 3.4.2 Global transit light curve modeling

We homogeneously analyzed all the transit light curves to retrieve the individual planetary parameters from the photometric datasets (i.e., CHEOPS, TESS, K2, HST and *Spitzer*)

<sup>6</sup>PAдова and TRIeste Stellar Evolutionary Code: <https://stev.oapd.inaf.it/cgi-bin/cmd>

<sup>7</sup><https://github.com/LucaMalavolta/PyORBIT>

<sup>8</sup>Here,  $f$  refers to the measured flux.

using PyORBIT. The transits were modeled with the batman package (Kreidberg et al. 2015), and for the *K2* transits we used a super-sampling factor of 30. We assumed circular orbits, by fixing the eccentricity value to zero, for the two planets. We fixed the orbital periods ( $P$ ) to the values we inferred from the CHEOPS pre-modeling i.e.,  $P_b = 15.571893 \pm 0.000068$ ,  $P_c = 31.70838 \pm 0.00041$  (see Sec. 3.4.1), in order to retrieve the transit timings of each individual event. We included a third-order polynomial temporal trend (4 free parameters) for each of the *K2*, *Spitzer*, and HST light curves. For all five instrument passbands, the stellar parameters (see Tab. 3.1) were used as Gaussian priors to compute the quadratic limb darkening (LD) coefficients with PyLDTk (Husser et al. 2013; Parviainen & Aigrain 2015). We used these computed values, with a conservative uncertainty of 0.05, as Gaussian priors in the global analysis, using the LD parameterization ( $q_1, q_2$ ) introduced by Kipping (2013). Gaussian priors were imposed on the stellar radius and mass based on the stellar spectroscopic analysis conducted in Section 3.3. Uninformative uniform priors were imposed on all other free parameters (see Tab. 3.5). The analysis had a total of 134 fitting parameters: 10 LD coefficients (two for CHEOPS, TESS, *K2*, *Spitzer*, and HST), four planetary parameters ( $b$ ,  $R_p/R_\star$  for -b and -c), 47 transit times ( $T_0$ ), stellar density ( $\rho_\star$ ), 12 jitter parameters (one for each telescope, and one for each TESS sector), and 60 ( $15 \times 4$ ) polynomial trend coefficients. Global parameter optimization was carried out using the PyDE<sup>9</sup> differential evolution algorithm (Storn & Price 1997; Parviainen et al. 2016), using 100 000 generations with a population of  $10 \times N_{\text{para}}$ , where  $N_{\text{para}}$  is the number of free parameters. The output parameters were used as the initial values for the Bayesian analysis, performed using the emcee package (Foreman-Mackey et al. 2013), which implements the affine invariant MCMC ensemble sampler (Goodman & Weare 2010). We performed an autocorrelation analysis on the chains and the chains were considered converged if they were longer than 100 times the estimated autocorrelation time and this estimate varied by less than 1%. We ran the sampler with  $10 \times n_{\text{dim}}$  walkers (where  $n_{\text{dim}}$  is the number of dimensions of the model) for 450 000 steps. We discarded the first 100 000 steps, assuring the convergence of the chains, and set a thinning factor of 100. All the fitted parameters and their corresponding priors as well as the derived posteriors are shown in Tab. 3.5. All the inferred central times of transit ( $T_0$ ) are displayed in Tabs. 3.3 and 3.4. We show the phase-folded light curves with the best fit transit model in Fig. 3.6.

### 3.4.3 Dynamical modeling with TRADES

When two neighboring planets are close to a mean motion resonance (MMR), their orbital periods approach a ratio of small integers ( $p/q$ ). To quantify the proximity to resonance, we used the fractional deviation  $\Delta$ , as introduced by Lithwick et al. (2012), defined as:

$$\Delta = \frac{P_{\text{out}}/P_{\text{in}}}{p/q} - 1, \quad (3.1)$$

where  $P_{\text{out}}$  and  $P_{\text{in}}$  are the orbital periods of the outer and inner planets, respectively. As discussed in Section 3.1, the periods of the two inner planets are near the 2:1 period commensurability ( $p=2, q=1$ ), with  $\Delta \approx 0.018$ , which suggests we might observe large TTV signals due to strong mutual gravitational interactions (Agol et al. 2005; Lithwick

<sup>9</sup><https://github.com/hpparvi/PyDE>

et al. 2012; Steffen et al. 2012). We dynamically simulated the TTV signals and integrated the system parameters of HIP 41378 b & c simultaneously fitting the retrieved  $T_0$ s, (see Section 3.4.2 and Tabs. 3.3-3.4), and RVs (see Section 3.2.6) using the N-body dynamical integrator TRADES<sup>10</sup> (Borsato et al. 2014, 2019, 2021, 2022; Nascimbeni et al. 2023; Borsato et al. 2024; Nascimbeni et al. 2024). We selected as the start of the integration and reference time  $T_{ref,dyn} = 2\,457\,137$  (BJD<sub>TDB</sub>), with the integration time ( $T_{int} = 3620$  days) chosen to cover the entire time span of all observations. Following the detection of an additional planetary RV signal by S19, with an estimated period of approximately 62 days, near the 2:1 period commensurability with planet c, we decided to investigate this possibility further by testing two models in our analysis.

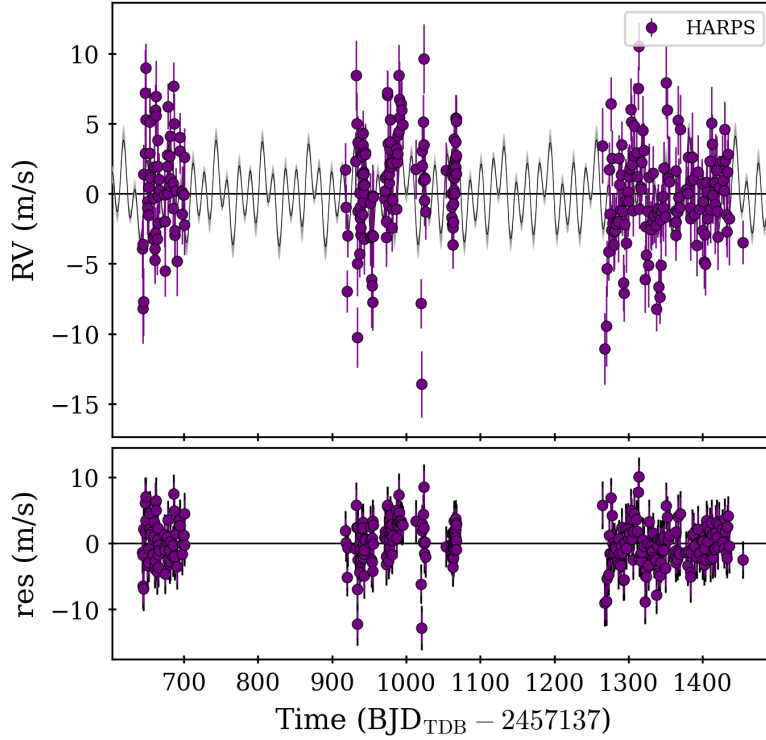


Figure 3.1: Radial velocities of HIP 41378. Upper panel: RV plot minus the offset  $\gamma$ . TRADES MAP model is shown as a black line, with the shaded grey areas indicating the  $1\sigma$ ,  $2\sigma$ , and  $3\sigma$  confidence intervals. HARPS observations are depicted as purple circles. Lower Panel: RV residuals after subtracting the model.

## Two-planet model

In the first configuration we tested a two-planet model formed by HIP 41378 b and HIP 41378 c. We used as fitting parameters the planetary-to-star mass ratio  $M_p/M_\star$ , the period  $P$ , the eccentricity  $e$ , and the mean longitude  $\lambda$ <sup>11</sup>. Rather than fitting eccentricity  $e$  and argument of periastron  $\omega$  individually, we used the parametrization  $(\sqrt{e} \cos \omega, \sqrt{e} \sin \omega)$ .

<sup>10</sup><https://github.com/lucaborsato/trades>

<sup>11</sup> $\lambda = \mathcal{M} + \omega + \Omega$ , where  $\mathcal{M}$  is the mean anomaly,  $\omega$  is the argument of periastron (or pericenter), and  $\Omega$  is the longitude of the ascending node.

The mass ratios are used as fitting parameters instead of absolute masses, since TTVs only provide constraints on the relative masses of the planets and the host star. We set the longitude of ascending node  $\Omega = 180^\circ$  for -b, and fit it for -c (following Winn 2010; Borsato et al. 2014). We fixed the planetary and stellar radii ( $R_p$ ,  $R_\star$ ), stellar mass ( $M_\star$ ) and the inclination  $i$ , according to the values from Tabs. 3.1 and 3.5. For the RV dataset we fit a jitter term ( $\sigma_j$ ) in  $\log_2$  and an offset ( $RV_\gamma$ ). We imposed half-Gaussian priors on the eccentricities following Van Eylen et al. (2019). To assess potential biases introduced by this choice, we performed an additional fit using uninformative-uniform priors on  $e$ . This alternative analysis yielded posteriors consistent within  $1\sigma$  but resulted in a higher BIC<sup>12</sup> value. When comparing models using the BIC, a lower value indicates a better fit to the data, accounting for the complexity of the model. Therefore, we chose to adopt the results from the model with the half-Gaussian prior as our reference solution. For each remaining parameter we imposed uniform-uninformative priors (see Tab. 3.6).

### Three-planet model

Building on the two-planet configuration, we performed a dynamical analysis by including an additional planet, HIP 41378 g. The setup for the three-planet model was identical to that of the two-planet model, with a few additional parameters introduced for the third planet. In contrast to the other planets, for planet g we additionally fit the inclination ( $i$ ). The prior ranges for these parameters were chosen to allow for both transiting and non-transiting orbital configurations. Half-Gaussian priors were applied to the eccentricities, and uninformative priors were used for the remaining parameters (see Tab. 3.6).

#### 3.4.4 Analysis

For both two- and three-planet models, we first ran PyDE with a population size of 120 (i.e. the number of different initial parameter sets) for 70 000 steps. The best-fit outputs from PyDE were then used as initial conditions for the EMCEE package, which we ran for 600 000 steps using 120 walkers, corresponding to 9 and 6 times the dimensionality (number of free parameters) in the respective models. Following the methodology described in Nascimbeni et al. (2024), we employed a combination of the differential evolution proposal (80% of the walkers; Nelson et al. 2014) and the snooker differential evolution proposal (20% of the walkers; ter Braak & Vrugt 2008) as the sampler within EMCEE.

We used a thinning factor of 100 and discarded 450 000 steps as burn-in, long after the chains converged according to the Geweke (Geweke 1991), Gelman-Rubin (Gelman & Rubin 1992), autocorrelation function (Goodman & Weare 2010), and visual inspection criteria. The uncertainty associated with each parameter was computed as the highest density interval (HDI) at the 68.27% credibility level from the marginalized posterior distribution, representing the most probable region of the posterior. Best-fit values were defined as the maximum a posteriori (MAP) estimates, computed from the posterior distributions and constrained to lie within the HDIs of the fitting parameters.

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<sup>12</sup>Bayesian information criterion (BIC; Schwarz 1978)



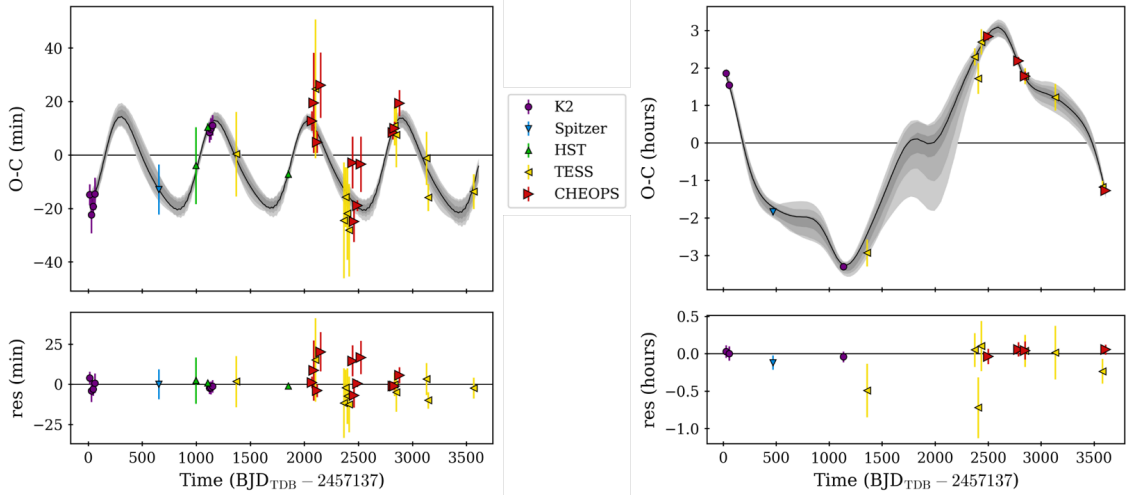


Figure 3.2: Observed-minus-Calculated (O-C) diagrams of HIP 41378 b (left) & c (right). Each dataset is plotted with a different marker and color. Upper panel: The best-fit TRADES model is shown as a black line, with the shaded grey areas indicating the  $1\sigma$ ,  $2\sigma$ , and  $3\sigma$  confidence intervals. Lower panel: Residuals with respect to the best-fit model.

### 3.5 Results

Using the N-body dynamical integrator within TRADES, we performed joint modeling of the TTV and RV signals, and successfully retrieved the orbital configuration of HIP 41378 b, HIP 41378 c and HIP 41378 g (see Figs. 3.1-3.2). The best-fit model was selected using both the BIC and the log Bayes factor, which provide complementary model comparison metrics. The comparison between the two-planet and three-planet models ( $\text{BIC}_{2p} = 4170.08$  and  $\text{BIC}_{3p} = 1353.72$ ) yields a difference of  $\Delta\text{BIC} = 2816.36$ , strongly favoring the inclusion of the third planet, HIP 41378 g. To strengthen this conclusion, we also computed the logarithm of the Bayes factor (Kass & Raftery 1995) between the two models, by using the approximation found on page seven of Shen & González (2021), obtaining  $\log \mathcal{B}_{3p,2p} = 1400$ , which provides decisive evidence in favor of the three-planet model. This confirms that the addition of HIP 41378 g significantly improves the fit and is statistically justified. Thereafter, we decided to adopt the posteriors of the three-planet model as reference hereafter in the paper. We were able to determine the planetary mass of HIP 41378 g with a  $\sim 6\sigma$  level of significance, enabled by the dynamical simultaneous modeling of both TTVs and RVs data. Our analysis places the orbital period of HIP 41378 g at approximately  $\sim 64$  days, close to the 2:1 period commensurability with HIP 41378 c ( $P_g/P_c \sim 2.04$ ), in agreement with the RV signal found by S19. The orbital solution shows a compact inner system comprising three sub-Neptunes, which are near a 4:2:1 period ratio. Our final posterior values along with the priors and the uncertainty intervals are presented in Tab. 3.6. Plots of the Observed-minus-Calculated (O-C) diagrams of both planets and the RV plots are shown in Figs. 3.1-3.2.

As a complementary result of our dynamical analysis, TRADES evaluates the Hill stability of the system using the AMD-Hill criterion (Eq. 26 Petit et al. 2018), which is based on the angular momentum deficit (AMD; Laskar 1997, Laskar 2000; Laskar &

Petit 2017). We find that the entire posterior distribution satisfies the AMD-Hill stability criterion, indicating the long-term dynamical stability of the posterior. However, to further assess the stability and chaotic behavior of the posterior solutions, considering effects of planet-planet interactions, mean-motion resonances and planetary ejections, we used the N-body integrator `rebound` (Rein & Liu 2012; Rein & Tamayo 2016). Specifically, we employed the Mean Exponential Growth factor of Nearby Orbits (MEGNO; or  $\langle Y \rangle$ ) chaos indicator (Cincotta & Simó 2000; Cincotta et al. 2003). A planetary system is considered to be in a stable configuration if it satisfies the condition  $\langle Y \rangle \lesssim 2$ , while a planet is considered as ejected if its semi-major axis exceeded 100 times that of planet c. We computed the orbits for a total of 100 Kyr using the symplectic integrator `WHFast`, with a step size corresponding to 10% of the orbital period of planet b. We obtained  $\langle Y \rangle \lesssim 2$  for the best-fit (MAP within HDI) solution indicating that the configuration is stable in the integrated time. We then checked a family of solutions randomly selected from our posterior distribution. After running the same integration for 200 solutions, we find that 87.5% of the simulations exhibited strong stable dynamics.

## 3.6 Discussion

Our discussion is divided into six parts. In Sect. 3.6.1, we contextualize the derived planetary parameters with literature values and the broader sub-Neptune population using the mass-radius diagram. The system’s potential architecture is discussed in 3.6.2. The interior composition of the planets is analyzed in 3.6.4.

### 3.6.1 Planets in context

When compared with the values reported by S19, we find some statistical discrepancies in the masses of planets b and c. S19 derived a mass for planet c of  $M_c = 4.4 \pm 1.1 M_\oplus$ , suggesting a low bulk density ( $\rho_c = 1.19 \pm 0.30 \text{ g cm}^{-3}$ ), which placed it among the sub-Neptune puffy population. This made it the second lowest-density planet in the system, alongside the super-puff HIP 41378 f ( $\rho_f = 0.09 \pm 0.02 \text{ g cm}^{-3}$ ), whose unusually low density has been proposed to result from the presence of opaque, oblique planetary rings (Piro & Vissapragada 2020; Akınanmi et al. 2020). In contrast, our updated mass for planet c ( $M_c = 6.53^{+1.33}_{-0.42} M_\oplus$ ) places it within the typical range for sub-Neptunes ( $\rho_c = 1.854^{+0.572}_{-0.031} \text{ g cm}^{-3}$ ), ruling out the puffy scenario (see Fig. 3.3). This reassessment of planet c highlights the potential for a similar reevaluation for HIP 41378 f as additional RV and photometry data become available, potentially refining its mass and density estimates.

Although S19 identified the RV signal of HIP 41378 g and provided a minimum mass estimate, they were unable to detect any transits in their available photometry. This is consistent with the duration of the K2 C5 campaign, which lasted 75 days, slightly longer than our inferred period of  $\sim 64$  days. In our dynamical analysis (see Sect. 3.4.3), we explored both transiting and non-transiting configurations for the planet. The resulting inclination of  $95^{+1}_{-10}$  deg suggests a non-transiting orbit. From our line of sight, any planet farther out than planet c (i.e., with a semimajor axis exceeding  $a_c = 34.60 R_\star$ ) will not transit its host star unless its orbital inclination lies within a narrow range,

$88.32^\circ < i_g < 91.68^\circ$ , as derived from  $\arccos(\pm b/34.60)$ , with  $b = (R_\star + R_g)/R_\star$ <sup>13</sup>. Supporting the results of the dynamical analysis, we detected no transits of HIP 41378 g in the newly available TESS and CHEOPS photometric data. These results differ from statistical studies on *Kepler* multi-planet systems, which have been shown to be largely coplanar with a typical scatter of  $\pm 3^\circ$  (Fang & Margot 2012; Weiss et al. 2023).

To compare the planets with the current sub-Neptune population and to provide an initial constraint on their possible bulk compositions, we placed the two planets in the mass-radius diagram (see Fig. 3.3). Since HIP 41378 g does not transit its radius remains undetermined; hence, we did not include it in the diagram. By placing the planets in the mass-radius diagram, we can see that they are consistent with the current sub-Neptune population. However the position of the planets does not allow us to uniquely determine their composition. We displayed the mass-radius models from Zeng et al. (2019) and Lopez & Fortney (2014), which account for a 50% water-world composition and an Earth-like core with different envelope compositions. The planets fall at the intersections of multiple composition tracks, making it challenging to break the degeneracy between H/He envelope and water-world compositions, based on mass and radius alone. For a more detailed analysis of their internal composition, see Sect. 3.6.4.

### 3.6.2 On the architecture of the planetary system

The HIP 41378 system hosts six planets, five of which transit the star along our line of sight. As of now, the periods of two outer planets, HIP 41378 d and HIP 41378 e, remain unresolved. A single transit of HIP 41378 e was observed during *K2* Campaign 5, preventing an estimation of its orbital period. On the other hand, HIP 41378 d was observed to transit during both *K2* campaigns (5 and 18), enabling the identification of a set of 23 orbital period aliases. The new TESS sector observations, combined with the findings of Sulis et al. (2024), effectively ruled out the shortest orbital periods for HIP 41378 d, narrowing the set of aliases to three values:  $\sim 278$ ,  $\sim 371$ , and  $\sim 1113$  days. Each of these periods places the planet near a first-order period commensurability with HIP 41378 f (i.e. 2:1, 3:2 and 1:2), which could explain the strong TTVs ( $> 4$  hours) observed for the planet (Bryant et al. 2021; Alam et al. 2022). This could suggest the potential existence of a second quasi-resonance chain involving the three outer planets.

Based on the possible orbital periods of the two unresolved outer planets, and the confirmed planetary signal of planet g, we suggest two dynamical configurations for the system: i) a system-wide quasi-resonant chain or ii) hierarchical multi-planet architecture. In the first scenario, the planets follow a continuous quasi-resonant chain, with period ratios that closely align with small integer values. This would suggest a dynamically structured system, where all the planets may have experienced convergent migration and undergone resonant capture (Wong & Lee 2024). This would imply the potential presence of additional, yet-undetected planets between the inner and outer regions, completing the resonance chain. In the second configuration, the system possesses a middle-gap, separating the three inner sub-Neptunes from the three outer Neptunes. As a result, the system is assumed to be hierarchical, meaning that it can be divided into two independently stable subsystems (Laskar & Petit 2017). In this scenario, the outer planets would be dynamically

<sup>13</sup>The radius of planet g was estimated using the Bayesian radius-density-mass relation for small planets implemented in *spright* (Parviainen et al. 2023), obtaining a value of  $2.42^{+0.5}_{-0.5} R_\oplus$

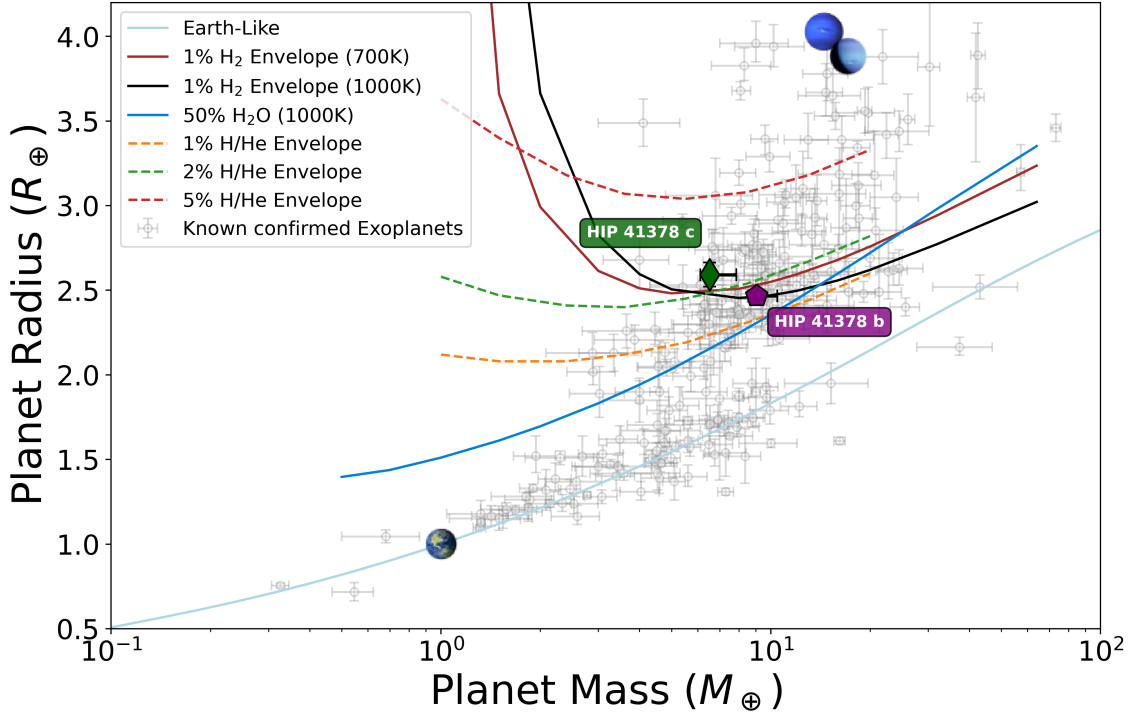


Figure 3.3: Mass-radius diagram including all confirmed planets with radii below  $4 R_{\oplus}$  with masses and radii measured to better than 30% precision (Grey points). Planet parameters are taken from the NASA Exoplanet Archive’s confirmed planets table, as queried on January 20, 2025. The purple pentagon represents the position of HIP 41378 b, the green diamond of HIP 41378 c. The color-coded lines show different theoretical mass–radius relations corresponding to the planet compositions taken from Zeng et al. (2019) (solid lines) and Lopez & Fortney (2014) (dashed lines; 1 Gyr, solar metallicity and incident flux of  $10 S_{\oplus}$ ). Also shown are Earth, Uranus and Neptune, for reference.

decoupled from the inner trio, suggesting that they should not significantly influence the observed TTV signals of the inner planets. Additionally, the three outer planets could be close to a resonant chain, potentially near a low-order period commensurability. This would suggest that, while the system remains hierarchical, the outer planets could still be dynamically linked through resonant interactions. Similar architectures have been observed in systems such as Kepler-90 (Cabrera et al. 2013), which hosts both 2:3:4 and 5:4 quasi-resonant chains, and HD 191939 (Orell-Miquel et al. 2023), exhibiting coupled 1:3:4 and 3:1 configurations. Further observations of the outer planets will be necessary to precisely constrain their orbital periods and determine the system’s unique dynamical configuration. The outer-system architecture will be further explored in Grouffal et al. (in prep.). To investigate the two hypotheses and put further constraints on the known outer planets (HIP 41378 d, HIP 41378 e, and HIP 41378 f), we conducted a four- and six-planet dynamical analysis with TRADES. This included testing for a hypothetical planet “h” situated between planets g and d. The setup mirrored the one used for HIP 41378 g, employing broad priors to explore a wide parameter space for radius, mass, and period, based on the findings of S19 and B19. However, we were unable to constrain the masses and orbital periods of the additional planets, resulting in poor fits for all planets, with

$\text{BIC}_{3p} \ll \text{BIC}_{6p}, \text{BIC}_{4p}$ .

For now, the planetary architecture for HIP 41378 remains an unresolved puzzle. However, the dynamical evidence of HIP 41378 g enables us to further investigate this peculiar multi-planet configuration. Given the limited constraints on the orbital architecture of the outer planets, we focused on the configuration of the inner planets. Following the classification scheme proposed by Howe et al. (2025), the inner planets display a closely spaced "peas-in-a-pod" configuration, indicating a high degree of uniformity in their orbital and physical properties. To measure the degree of this similarity, we applied the approach of Otegi et al. (2022). Specifically, we evaluated the distances in logarithmic space for the mass ( $D_M$ ), radius ( $D_R$ ), and their combined global distance ( $D$ ). In this metric, lower values correspond to greater similarity. According to our calculated values of  $D_R = 0.007$ ,  $D_M = 0.08$ , and  $D = 0.08$ , the three planets exhibit strong similarity. These results classify the inner system of HIP 41378 as the fifth<sup>14</sup> most uniform in the sample of 48 systems analyzed by Otegi et al. (2022). This reinforces the "closed-spaced peas-in-a-pod" scenario (Weiss et al. 2018; Howe et al. 2025) and potentially hints at a common formation pathway. Furthermore, consistent with the trend reported by Otegi et al. (2022), the inner planetary system shows greater similarity in radius than in mass. As pointed out by the authors, this could be attributed to the similarity in planetary density within a system. Given that the density is three times more sensitive to radius variations than to mass variations, it is expected to have a stronger uniformity in radius than in mass.

### 3.6.3 Investigation on the mean-motion resonant state

The inferred orbital period of HIP 41378 g, near a 2:1 period commensurability with planet c, positions the inner HIP 41378 system close to a three-body 4:2:1 resonant chain. Dynamical configurations in or near MMRs are expected to arise during the early stages of planetary system formation, within the gas-rich protoplanetary disk. For low-mass planets these configurations are thought to result from Type-I convergent migration in gas-rich disks, during which the forming planets are captured in resonance (e.g., Malhotra 1993b; Kley & Nelson 2012; Delisle 2017; Izidoro et al. 2017; MacDonald & Dawson 2018). To investigate whether the three-body chain is in a true mean-motion resonance, we studied the evolution of the three-body angle  $\Psi_{123}$ . This angle is defined by the difference between two critical resonant angles:

$$\begin{aligned}\phi_{12} &= 2\lambda_c - \lambda_b - \varpi_c, \\ \phi_{23} &= 2\lambda_g - \lambda_c + \varpi_c, \\ \Psi_{123} &= \phi_{12} - \phi_{23} = 3\lambda_c - \lambda_b - 2\lambda_g.\end{aligned}\tag{3.2}$$

For a (2:1, 2:1) resonant configuration, Siegel & Fabrycky (2021) predict that the three-body angle should librate (oscillate around a fixed value) around  $180^\circ$ . We integrated the  $\text{MAP}_{\text{HDI}}$  solutions using the N-body code `rebound` (Rein & Liu 2012) and the symplectic integrator `WHFast` (Rein & Tamayo 2016), for a total duration of 10 000 years. Our results, depicted in Fig. 3.4, indicate that the three planets are out of resonance, with the three-body angle circulating from 0 to  $360^\circ$ .

<sup>14</sup>The four above are: Kepler-60, Kepler-29, TOI 763 and L 98-59

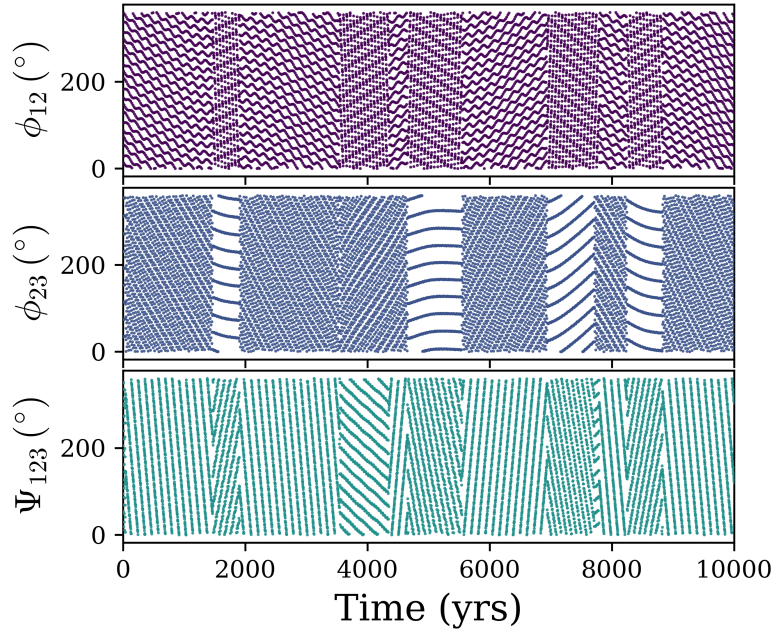


Figure 3.4: Three-body Laplace resonant angles evolution for HIP 41378 b, c and g, for the MAP<sub>HDI</sub> solutions. The top two panels show the evolution of the critical angles  $\phi_{12}$  and  $\phi_{23}$ . The bottom panel shows the three-body angle, which is a linear combination of the mean longitudes of the planets.

### 3.6.4 Interior bulk composition

Based on the derived planetary parameters, we used the internal structure modeling framework `plaNETic`<sup>15</sup> (Egger et al. 2024) to infer the interior compositions of HIP 41378 b and HIP 41378 c. `plaNETic` uses a neural network as a surrogate model for the planetary structure forward model BICEPS (Haldemann et al. 2024) to speed up the inference process, which allows for a fast, but still reliable analysis. The modeled planets are assumed to consist of an envelope of uniformly mixed H/He and water, a mantle layer composed of silicon, magnesium, and iron oxides, and an inner iron core, diluted with up to 19% sulfur as a placeholder for any lighter elements. Both observed planets are modeled simultaneously.

Since this remains a highly degenerate problem with many possible interior structures compatible with the observed planetary bulk properties, the outcome of the inference process depends to a certain extent on the chosen priors. We therefore ran six models assuming different combinations of priors, compatible with different assumptions on the system’s formation and evolution history. First, we consider two distinct priors for the planet’s water content: one based on a formation scenario beyond the ice-line (Case A, water-rich) and another corresponding to formation within the ice-line (Case B, water-poor). For each of these water priors, we consider three different assumptions for the planetary Si/Mg/Fe ratios. In the first case, we assume the planet’s composition directly reflects the stellar Si/Mg/Fe ratios (Thiabaud et al. 2015). In the second case, we account for iron enrichment relative to the host star using the empirical fit from (Adibekyan et al.

<sup>15</sup><https://github.com/joannegger/plaNETic>

2021). In the third case, we model the planet’s composition independently of the stellar ratios, sampling the Si, Mg, and Fe molar fractions uniformly from the simplex where their sum is 1, with an upper limit of 0.75 for Fe. A detailed description of these priors can be found in (Egger et al. 2024).

The resulting posterior distributions for the most important internal structure parameters are visualized in Figs. 3.11 and 3.12, with the results for the full list of internal structure parameters summarized in Tabs. 3.7 and 3.8. We do not constrain the core and mantle layer mass fractions for either planet; the inferred posteriors mostly match the priors. In the water-rich case, we infer envelope mass fractions between 38 and 42% for planet b and of 31% for planet c, with envelope water mass fractions of almost 100% for planet b and around 90% for planet c. In the water-poor case, on the other hand, we constrain the envelope mass fractions quite well with values of the order on 0.3 to 0.6% for planet b and 0.8 to 1.2% for planet c. A future JWST transmission spectrum of HIP 41378 b and HIP 41378 c could help resolve this degeneracy by directly probing the atmospheric composition of their upper envelope layers. This possibility is explored in Sect. 3.6.6.

### 3.6.5 Primordial atmospheric evolution

To assess the possible evolution scenarios of the primordial atmospheres of planets b and c, we employed the same approach as described in Krenn et al. (2024). Namely, we used the atmospheric evolution framework developed in Kubyshkina & Vidotto (2021) for H-He-dominated (water-poor) atmospheres. This framework employs MESA (Modules for Experiments in Stellar Astrophysics; Paxton et al. 2011, 2013, 2018, 2019) to track the dissipation of the planetary post-formation luminosity, contributing to the evolution of planetary radii, and the atmospheric escape rates based on the grid of 1D hydrodynamic upper atmosphere models presented in Kubyshkina et al. (2018); Kubyshkina & Fossati (2021). For the latter, we employ the machine-learning-based algorithm described in Reza et al. (2025), which shows a better accuracy compared to the previously used interpolation methods (Kubyshkina et al. 2018).

For the stellar evolution model, providing inputs both to MESA (stellar bolometric luminosity  $L_{\text{bol}}$  versus age) and the atmospheric escape model ( $L_{\text{bol}}$  and XUV, X-ray plus extreme ultraviolet, luminosity  $L_{\text{XUV}}$  versus age), we employ the Mors stellar evolution code (Johnstone et al. 2021; Spada et al. 2013). As there are no constraints available for the X-ray luminosity of HIP 41378, to inform our models, we use solely the information available for stellar rotation. Given the relatively small age of the system ( $\lesssim 2.5$  Gyr) and relatively slow rotation, we find that HIP 41378 was unlikely a very fast rotator at early ages. Therefore, we exclude such stellar models from our analysis and only consider 4 initial (at 150 Myr;  $P_{\text{rot}}^{150}$ ) stellar rotation periods of 5-20 days. Finally, we note that for stellar mass we employ the value of  $1.2 M_{\odot}$ , which lies at the lower boundary of the  $1\text{-}\sigma$  estimate for HIP 41378, because it is the highest mass available for the grid of stellar isochrones used by the Mors code (Spada et al. 2013). This is not expected to affect the results considerably because in the mass range  $1.0\text{-}1.2 M_{\odot}$  internal stellar parameters change smoothly and stellar XUV radiation depends on rotation period much stronger than on stellar mass.

As our evolution framework is too computationally expensive, we apply a grid-like



approach, as described in detail in Krenn et al. (2024). For the system parameters that are constrained well and/or have a weak influence on the results, we use single values: stellar mass of  $M_* = 1.2 M_\odot$ , orbital separations of  $a_b = \text{AU}$  and  $a_c = \text{AU}$ , and lifetime of the protoplanetary disc of 5 Myr (which is the starting time of our simulations). Similarly, for initial planetary luminosities, we adopt the values naturally derived by MESA (which are the extrapolation from the stellar evolution tracks ?) and do not test additional scenarios (as their effect vanishes on timescales of a few tens of Myr; e.g. Owen 2020; Kubyskhina & Vidotto 2021). For the parameters that are poorly constrained and/or strongly impact the atmospheric evolution, we explore a range of values. For planetary mass, we assume that the present-day mass is mostly defined by the planet’s solids (which we refer to here as “core”) and the atmosphere’s mass contributes not more than about a percent (which is consistent with the predictions of the interior models for the case B). Thus, we assume that the core mass remains the same throughout the evolution and  $M_{\text{core}}^0 \simeq M_{\text{pl}}^{\text{obs}}$ ; For both planets we consider a range of values for  $M_{\text{core}}^0$  varying it within  $1-\sigma$  of what obtained from the observations (with a step of  $\sim 0.2 M_\oplus$ ). For each of these values, we further consider the initial atmospheric mass fractions  $f_{\text{at}}^0$  between 0.005 and 0.5 (30 and 26 values for planets b and c, respectively, logarithmically distributed). Thus, the initial planetary masses are set as  $M_{\text{pl}}^0 = M_{\text{core}}^0 + M_{\text{atm}}^0 = M_{\text{core}}^0 / (1 - f_{\text{at}}^0)$  and span the intervals of  $8.55\text{--}17.36 M_\oplus$  for planet b and  $5.84\text{--}12.86 M_\oplus$  for planet c. The initial entropies at the core-atmosphere boundary (quantifying the initial planetary luminosities) vary between  $7.0\text{--}8.2 k_b/\text{baryon}$  for planet b and  $7.2\text{--}8.4 k_b/\text{baryon}$  for planet c, where the smallest value corresponds to the lowest core mass and smallest atmospheric mass fraction.

After setting the initial parameters, we evolve the planets under different stellar XUV conditions, obtaining in the end over 1000 evolutionary models for each planet, with predictions of how  $R_{\text{pl}}(\text{age})$  depends on  $M_{\text{pl}}(\text{age})$  being part of the output. We then compare these to the observational constraints on planetary masses, radii, and the age of the system to find which combinations of initial parameters allow us to reproduce the planet-day planets. To outline the boundaries of the fitting parameter intervals more accurately, we interpolate our grid of evolutionary models on a finer grid of  $M_{\text{pl}}^0$  and  $f_{\text{at}}^0$  ( $5 \times$  nodes compared to the original grid). Furthermore, to aid the comparison, we split the 1-sigma interval of the age constraint of HIP 41378 system in 100 bins and performed the comparison in individual bins. We present the summary of our results in Fig. 3.5, which represent an image showing for which fraction  $f_{\text{age}}$  of the age bins considered a given combination of  $M_{\text{pl}}^0$  and  $f_{\text{at}}^0$  allows reproducing the present day radius and mass for all considered  $P_{\text{rot}}^{150}$ . We note, that, though normalized to 1, this value is not equivalent to the posterior probability resolved in a Monte Carlo algorithm (which cannot be applied with our model due to high computational costs); instead, it can be seen as a proxy for the stability of the given atmospheric configuration (low positive number implies that the planetary parameters change significantly within 1.4 Gyr comprising the uncertainty on the age of HIP 41378).

For HIP 41378 b (Fig. 3.5 (left); note that we only show results for the parameter region that allows to reproduce present-day parameters, while the whole parameter range that we examined is much broader), we obtain a very narrow constraint on the initial atmospheric mass fractions, which changes only slightly with different assumptions on stellar rotation. Thus, the overall constraint spans between 0.9% to 2.5% of planetary mass, with the full span corresponding to the initial stellar rotation period of 5 days and an even narrower



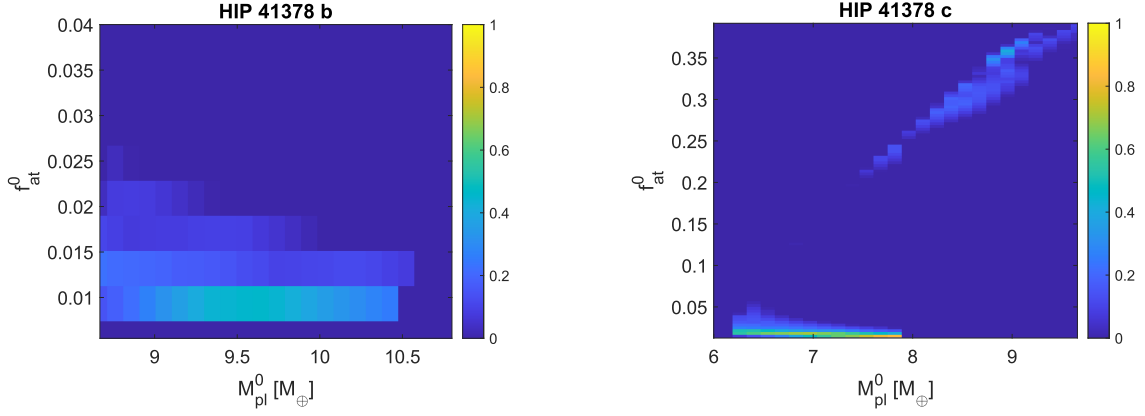


Figure 3.5: The fraction of the age bins where the given combination of  $M_{\text{pl}}^0$  (x-axis) and  $f_{\text{at}}^0$  (y-axis) allows reproducing the parameters of HIP 41378 b and HIP 41378 c for the whole range of initial rotation periods of HIP 41378 considered here.

constraint of 0.9-1.3‰ to 20 days. These parameters are consistent with the assumption of a planet with a H-He-dominated primordial atmosphere that formed in situ (within the snow line, e.g. Mordasini 2020). Consequently, the initial mass of the planet had to be very close to the present-day values, 8.6-10.5  $M_{\oplus}$ . It indicates that the atmospheric mass loss from the planet was rather low throughout the evolution, even in case of a relatively fast rotator.

As HIP 41378 c orbits significantly farther away from the star than HIP 41378 b ( $P_c \sim 2P_b$ ), it receives even less XUV radiation (which is the main driver of atmospheric mass loss on long timescales). However, the mass of HIP 41378 c is significantly lower than that of the planet b; therefore, the resulting atmospheric mass-loss rates from the planet are higher. This leads to a more peculiar shape of the parameter regions allowing reproducing the present-day mass and radius of the planet (see Fig. 3.5, right panel). Specifically, we find two different groups of “allowed” initial parameters, widely separated in the parameter space in the case of a moderately or slowly rotating star ( $P_{\text{rot}}^{150} \geq 10$  days). The first group is similar to the predictions for HIP 41378 b: the planet had to start with parameters in a relatively narrow range, close to the present day values ( $M_{\text{pl}}^0 \sim 6.2\text{-}7.9 M_{\oplus}$  and  $f_{\text{at}}^0 \sim 1.25\text{-}5.6\%$ ), with initial atmospheric mass fraction increasing with decreasing  $M_{\text{pl}}^0$  and  $P_{\text{rot}}^{150}$ . In all stellar rotation scenarios, the most stable configuration is achieved around  $f_{\text{at}}^0 \sim 1.6\text{-}1.9\%$ .

The second group is shaped by much larger initial atmospheric mass fractions and planetary masses. For slow rotators ( $P_{\text{rot}}^{150} \geq 15$  days), it occupies the space between  $f_{\text{at}}^0 \sim 30\text{-}38\%$  and  $M_{\text{pl}}^0 \sim 8.8\text{-}9.5 M_{\oplus}$ . For faster rotators, it extends towards the lower values of mass and atmospheric mass fractions ( $f_{\text{at}}^0 \sim 20\text{-}38\%$  and  $M_{\text{pl}}^0 \sim 7.5\text{-}9.5 M_{\oplus}$ ) but remains separated from the first group of compact initial atmospheres. This is the result of the non-linear dependence of the atmospheric evaporation timescale (as proxy of the atmospheric stability) on the initial atmospheric mass fraction for low-mass close-in planets. This effect was considered in more detail in Kubyschkina & Vidotto (2021). We note that this “puffy” brunch in our predictions for the initial planetary parameters corresponds to a

narrow range of core masses (i.e. present-day masses,  $\sim M_{\text{pl}}^0(1 - f_{\text{at}}^0)$ ) of  $\sim 5.8\text{--}6.2 M_{\oplus}$  (and even  $\sim 5.8\text{--}6 M_{\oplus}$  for  $P_{\text{rot}}^{150} \geq 10$  days). Furthermore, due to the strong correlation between the planetary radius (hence, atmospheric escape rate) and the internal temperature of the young planets, the specific position of this brunch in  $M_{\text{pl}}^0\text{--}f_{\text{at}}^0$  plane depends on our assumption on the planet’s post-formation luminosity (core entropy). This, together with the stability parameter shown in Fig. 3.5, suggests that the compact initial atmospheres and overall low mass-loss over the planet’s lifetime are the most probable scenario for both planets in HIP 41378 system.

### 3.6.6 Atmospheric characterization prospects

Atmospheric characterization of HIP 41378 b and HIP 41378 c with JWST could present a unique opportunity to study the atmospheric evolution, as well as to constrain their interior compositions (see Sect. 3.6.4). To evaluate their potential for transmission spectroscopy, we first computed the zero albedo equilibrium temperature (cf. Eq. 4 from Cowan & Agol 2011 and subsequently the Transmission Spectroscopy Metric (TSM; Kempton et al. 2018). While both planets fall below the nominal TSM threshold for ideal JWST candidates ( $\text{TSM} \lesssim 90$ ), the unique characteristics and significant scientific interest of the HIP 41378 system warranted a more detailed investigation. Therefore, we performed comprehensive spectral simulations across a suite of atmospheric scenarios to assess their true potential for JWST observations.

Edwards et al. (2023) previously demonstrated that HST observations of HIP 41378 b did not allow for significant molecular detections, with a flat atmospheric model, with no molecular absorption, being preferred. Our goal is to determine whether JWST is able of detecting molecular signatures in planet b and c, which would allow to constrain the atmospheric evolution scenarios described in Sect. 3.6.5. For our simulations, we adopted a solar metallicity ( $Z = Z_{\odot}$ ) atmosphere in chemical equilibrium for both planets. This choice is compatible with the value found by Edwards et al. (2023) for planet b and with a primordial atmosphere.

We generated the corresponding synthetic transmission spectra using the TauREx3 1D isothermal atmospheric model (Al-Refaie et al. 2021). Equilibrium chemistry calculations were performed with FastChem (Stock et al. 2018) via the `fastchem`<sup>16</sup> plugin, incorporating all available gases. Subsequently, we utilized GenTSO (Cubillos 2024), a software specifically designed for simulating JWST spectroscopic observations of exoplanetary atmospheres, to generate mock observations from these two synthetic spectra (one for each planet). For all scenarios, we adopted a specific NIRSpec instrument configuration, chosen to provide a comparison with the HST WFC3 instrument wavelength domain. This configuration comprised NIRSpec in bright object time-series (BOTS) mode, equipped with the `g140h` disperser (selected to limit detector saturation) and `f100lp` transmission filter, utilizing the `s1600a1` aperture, `sub2048` subarray, and `nrsrapid` read mode. Each simulated observation was based on a single transit with a baseline of  $1.75 T_{14}$ . To reduce uncertainties on transit depth, we binned the simulated observations to a spectral resolution of  $R = 500$ . The resulting transmission spectra for planets b and c are presented in Figs. 3.13a and 3.13b, respectively.

<sup>16</sup><https://github.com/ucl-exoplanets/taurex-fastchem>

To test the JWST capability to detect molecular features in HIP 41378 b and c, we followed a similar strategy to Edwards et al. (2023). This involved comparing a `fastchem` equilibrium chemistry model with a featureless (flat) spectrum model. We performed these retrievals using the Nested Sampling algorithm (Skilling 2006) within the `pymultinest` (Buchner et al. 2014) package with 1000 live points. For both planets, the equilibrium chemistry and flat models were compared using the logarithmic Bayes factor (Kass & Raftery 1995; Trotta 2007). In both cases, the  $\log \mathcal{B}_{\text{molecules,flat}} > 5$  strongly favoring the chemical equilibrium model over the flat one. This result confirms the capability of NIRSpec to detect molecular features in the atmospheres of planets b and c, thus enabling detailed studies of their atmospheric composition.

The results of our atmospheric retrievals confirm the need for high-sensitivity instruments like NIRSpec@JWST for precise atmospheric characterizations, allowing the detection of molecular features necessary to understand how the atmosphere of exoplanets evolved. Furthermore, they demonstrate that HIP 41378 b and HIP 41378 c are promising candidates for future atmospheric analysis, despite the low TSM, to constrain their bulk composition, formation and evolution scenarios.

### 3.7 Summary and conclusions

Using CHEOPS observations, TESS sectors, and archival data, we conducted a dynamical analysis of the two inner sub-Neptune planets transiting the bright star HIP 41378 ( $m_V = 8.9$  mag). We report the detection of large TTVs in the multi-planet HIP 41378 system, with amplitudes of 30 minutes and  $\gtrsim 3$  hours for planets b and c, respectively (see Fig. 3.2). Combining these TTVs with RV data, we significantly refined the planetary parameters (see Tabs. 3.5–3.6) and dynamically confirmed the additional non-transiting planet, HIP 41378 g, which lies close to the 2:1 period commensurability with planet c ( $P_g/P_c \sim 2.04$ ), suggesting a near 4:2:1 resonant chain for the inner planets. This detection raises further questions regarding the overall architecture which remains only partially resolved, with the orbital properties of two long-period planets (HIP 41378 d and e) yet to be constrained.

Our interior structure analysis revealed significant degeneracy in the interior structures of HIP 41378 b and c, with solutions heavily dependent on formation assumptions, highlighting the compositional degeneracy inherent to sub-Neptunes (Figs. 3.11–3.12). Water-rich scenarios suggest  $\sim 31$ – $42\%$  water-dominated envelopes, while water-poor cases yield compact H/He envelopes ( $\sim 0.3$ – $1\%$ ). These ambiguities highlight the need for JWST atmospheric spectroscopy to distinguish between competing models. For sub-Neptunes such as HIP 41378 b and HIP 41378 c, mass measurements paired with atmospheric studies will help resolve the compositional degeneracy between gas dwarfs (rocky planets with H/He envelopes; Lopez & Fortney 2014; Rogers et al. 2023) and water worlds (rocky planets with water-rich compositions; Léger et al. 2004; Dorn & Lichtenberg 2021; Aguichine et al. 2021; Luque & Pallé 2022). Additionally, by modeling atmospheric evolution, we showed that both sub-Neptunes can be explained by a scenario in where they formed with H-He atmospheres containing minor, solar-like metal abundances. If this was the case, they were most likely formed with compact atmospheres (with initial atmospheric mass fractions  $f_{\text{at}}^0 \sim 0.5$ – $5\%$ ) roughly consistent with the predictions of formation models (e.g. Mordasini 2020; Emsenhuber et al. 2021). With smaller probability, planet c could also

be formed with  $\sim 30\%$  of mass in H-He atmosphere if the actual planet's mass is close to the lower boundary of the observational constraint (see details in 3.6.5).

To further investigate these interior composition and atmospheric formation and evolution scenarios, we simulated observations with NIRSpec@JWST. Our simulations revealed that atmospheric characterization with JWST can allow the detection of molecular features in both planets. These results highlight that atmospheric characterization with JWST can provide key insights into their composition, formation, and evolution. The next central times of transit of planet b and c observable with JWST are reported in Tab. 3.9. Lastly, HIP 41378 will be not re-observed by *TESS* in year 8. This calls for new observations that could shed light into the possible quasi-resonant chain of the outer system, by exploring the possible period alias of the transiting HIP 41378 d or even detect another transit of HIP 41378 e.

### 3.8 Additional Tables and Figures

Table 3.2: Log of CHEOPS observations.

| VISIT ID | Planet | File Key                   | Start date<br>(UTC) | Duration<br>(h) | Number of Frames | Efficiency<br>(%) |
|----------|--------|----------------------------|---------------------|-----------------|------------------|-------------------|
| 1        | -b     | CH_PR100025_TG005501_V0300 | 2020-12-23T21:03    | 10.7            | 588              | 55.7              |
| 2        | -b     | CH_PR100025_TG005201_V0300 | 2021-01-08T20:08    | 6.49            | 366              | 58.21             |
| 3        | -b     | CH_PR100025_TG005701_V0300 | 2021-02-08T17:20    | 10.9            | 672              | 63.83             |
| 4        | -b     | CH_PR100025_TG005702_V0300 | 2021-03-11T22:16    | 12.04           | 671              | 55.18             |
| 5        | -b     | CH_PR100025_TG006501_V0300 | 2022-01-01T20:18    | 10.77           | 635              | 60.10             |
| 6        | -b     | CH_PR100025_TG006502_V0300 | 2022-01-17T07:26    | 10.68           | 616              | 59.68             |
| 7        | -b     | CH_PR100025_TG006503_V0300 | 2022-02-17T10:51    | 11.42           | 648              | 54.71             |
| 8        | -c     | CH_PR100025_TG006901_V0300 | 2022-02-26T00:11    | 10.84           | 662              | 62.90             |
| 9        | -b     | CH_PR100025_TG006801_V0300 | 2022-03-20T15:25    | 11.40           | 536              | 46.11             |
| 10       | -c     | CH_PR100025_TG006902_V0300 | 2022-12-08T10:11    | 11.42           | 562              | 49.17             |
| 11       | -b     | CH_PR100025_TG006802_V0300 | 2023-01-10T12:28    | 10.68           | 653              | 62.75             |
| 12       | -b     | CH_PR100025_TG006803_V0300 | 2023-01-25T23:11    | 10.87           | 650              | 60.49             |
| 13       | -c     | CH_PR100025_TG006903_V0300 | 2023-02-09T20:51    | 10.92           | 681              | 60.64             |
| 14       | -b     | CH_PR100025_TG006904_V0300 | 2023-03-13T14:31    | 15.69           | 823              | 52.09             |
| 15       | -c     | CH_PR140080_TG008101_V0300 | 2025-03-11T15:24    | 13.03           | 724              | 44.85             |

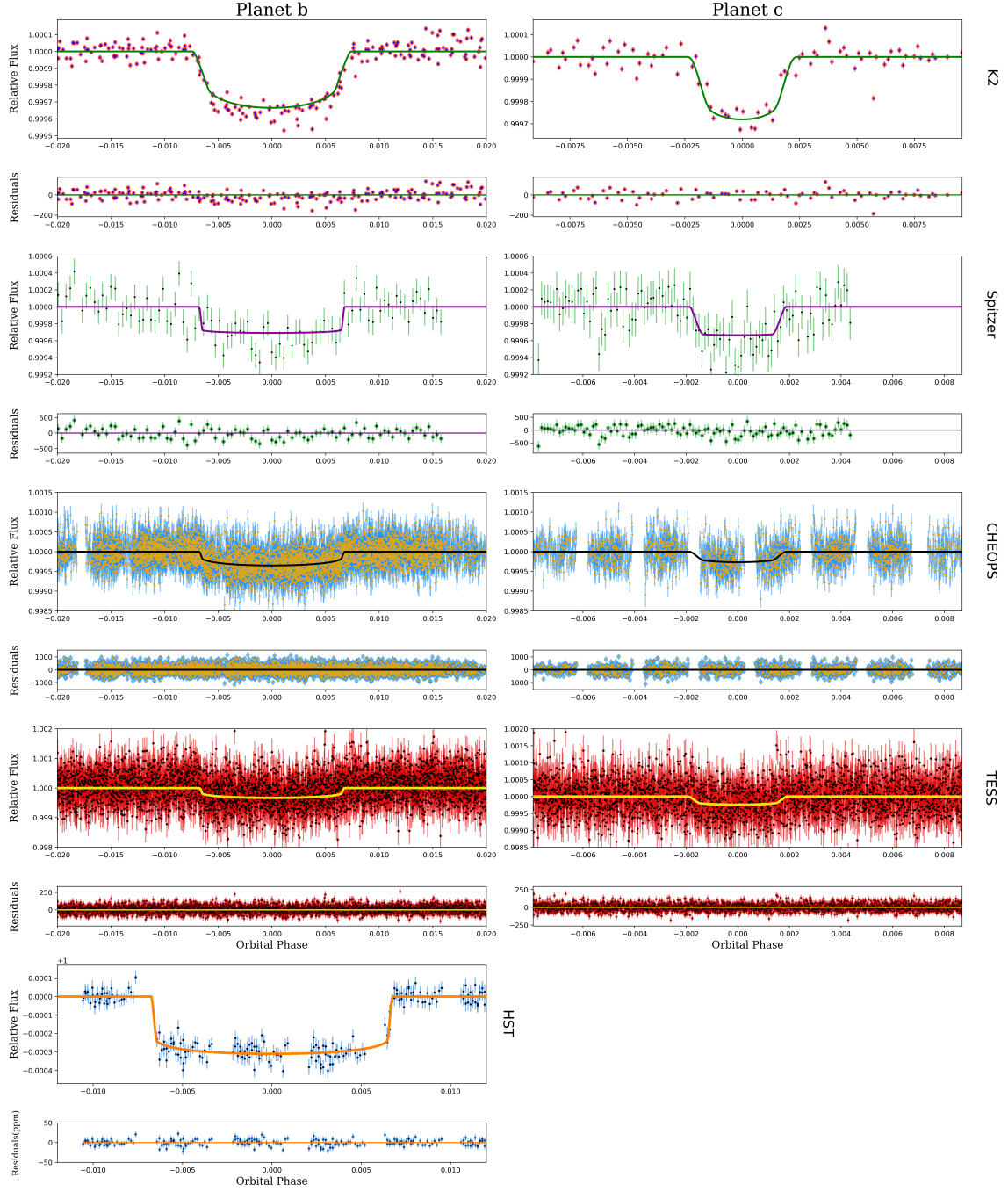


Figure 3.6: Phase folded light-curves of HIP 41378 b & c, combining observations from *K2*, *Spitzer*, *HST*, *CHEOPS*, and *TESS*. The oversampled best-fit transit models are overlaid on the light curves.

Table 3.3: Transit times of HIP 41378 b from the global photometric analysis with PyORBIT.

| $T_0$ (BJD <sub>TDB</sub> ) | $\sigma_{T_0}$ (days) | O-C (minutes) | Telescope |
|-----------------------------|-----------------------|---------------|-----------|
| 2 457 152.2847              | 0.0032                | −7.37         | <i>K2</i> |
| 2 457 167.8506              | 0.0035                | −15.89        | <i>K2</i> |
| 2 457 183.4244              | 0.0031                | −13.03        | <i>K2</i> |
| 2 457 198.9994              | 0.0044                | −8.44         | <i>K2</i> |
| 2 457 790.7293              | 0.0061                | −6.99         | Spitzer   |
| 2 458 133.3139              | 0.009                 | −0.21         | HST       |
| 2 458 242.3270              | 0.0008                | 14.78         | HST       |
| 2 458 257.8976              | 0.0031                | 13.03         | <i>K2</i> |
| 2 458 273.4731              | 0.0032                | 18.34         | <i>K2</i> |
| 2 458 289.0429              | 0.0032                | 15.44         | <i>K2</i> |
| 2 458 507.0416              | 0.015                 | 5.82          | TESS      |
| 2 458 989.7607              | 0.0008                | −4.45         | HST       |
| 2 459 207.7792              | 0.0017                | 14.47         | CHEOPS    |
| 2 459 223.3482              | 0.011                 | 10.42         | CHEOPS    |
| 2 459 238.9280              | 0.016                 | 21.92         | TESS      |
| 2 459 254.4894              | 0.0025                | 6.92          | CHEOPS    |
| 2 459 285.6473              | 0.0085                | 27.48         | CHEOPS    |
| 2 459 503.6167              | 0.016                 | −24.34        | TESS      |
| 2 459 519.1961              | 0.0088                | −13.41        | TESS      |
| 2 459 534.7626              | 0.012                 | −21.06        | TESS      |
| 2 459 581.4883              | 0.0037                | −6.29         | CHEOPS    |
| 2 459 597.0474              | 0.004                 | −24.60        | CHEOPS    |
| 2 459 628.1952              | 0.0012                | −18.58        | CHEOPS    |
| 2 459 659.3510              | 0.0083                | −1.05         | CHEOPS    |
| 2 459 955.2220              | 0.0018                | 8.38          | CHEOPS    |
| 2 459 970.7955              | 0.0044                | 10.81         | TESS      |
| 2 459 970.7947              | 0.0013                | 9.66          | CHEOPS    |
| 2 459 986.3647              | 0.0083                | 7.04          | TESS      |
| 2 460 017.5170              | 0.0029                | 19.53         | CHEOPS    |
| 2 460 266.6491              | 0.012                 | −4.82         | TESS      |
| 2 460 282.2123              | 0.0035                | −17.22        | TESS      |
| 2 460 702.6519              | 0.0049                | −16.29        | TESS      |

The O-C values (third column) are computed with respect to the linear ephemeris:

$$T_{\text{ref}} = 2\,457\,152.2898 \pm 0.0039 \text{ BJD}_{\text{TDB}}$$

$$P_{\text{lin}} = 15.571831 \pm 0.000029 \text{ days.}$$

The transit times are given in the BJD<sub>TDB</sub> standard (Eastman et al. 2010); the second column reports the associated 1- $\sigma$  error.

Table 3.4: Transit times of HIP 41378 c from the global photometric analysis with PYORBIT.

| $T_0$ (BJD <sub>TDB</sub> ) | $\sigma_{T0}$ (days) | O-C (minutes) | Telescope |
|-----------------------------|----------------------|---------------|-----------|
| 2 457 163.1667              | 0.0041               | 111.67        | <i>K2</i> |
| 2 457 194.8666              | 0.0049               | 93.28         | <i>K2</i> |
| 2 457 606.9849              | 0.0041               | −117.49       | Spitzer   |
| 2 458 272.8811              | 0.0037               | −218.00       | <i>K2</i> |
| 2 458 494.8820              | 0.018                | −200.39       | TESS      |
| 2 459 509.8920              | 0.0099               | 94.32         | TESS      |
| 2 459 541.5870              | 0.019                | 68.88         | TESS      |
| 2 459 573.3330              | 0.017                | 116.88        | TESS      |
| 2 459 636.7646              | 0.0038               | 125.90        | CHEOPS    |
| 2 459 922.1444              | 0.0038               | 76.65         | CHEOPS    |
| 2 459 985.5542              | 0.0088               | 54.28         | CHEOPS    |
| 2 459 985.5565              | 0.0042               | 57.60         | TESS      |
| 2 460 270.9410              | 0.013                | 15.11         | TESS      |
| 2 460 714.8139              | 0.0059               | −135.27       | TESS      |
| 2 460 746.5209              | 0.0028               | −143.43       | CHEOPS    |

The O-C values (third column) are computed with respect to the linear ephemeris:

$$T_{\text{ref}} = 2\,457\,163.089 \pm 0.047 \text{ BJD}_{\text{TDB}}$$

$$P_{\text{lin}} = 31.71266 \pm 0.00063 \text{ days.}$$

The transit times are given in the BJD<sub>TDB</sub> standard (Eastman et al. 2010); the second column reports the associated 1- $\sigma$  error.



Table 3.5: Posteriors and derived orbital parameters for HIP 41378 b & c from the global photometric analysis with PyORBIT, presented in Sect. 3.4.2

| Parameter                                              | Unit             | Prior                                 | Posterior value                     |
|--------------------------------------------------------|------------------|---------------------------------------|-------------------------------------|
| <i>HIP 41378 b</i>                                     |                  |                                       |                                     |
| FITTED PARAMETERS                                      |                  |                                       |                                     |
| Orbital Period ( $P$ )                                 | [days]           | (fixed)                               | $15.571893^{+0.000068}_{-0.000053}$ |
| Impact Parameter ( $b$ )                               | –                | $\mathcal{U}(0, 1 + (R_\star/R_p)/2)$ | $0.445^{+0.020}_{-0.023}$           |
| Planet-star radius ratio ( $R_p/R_\star$ )             | –                | $\mathcal{U}(0, 0.5)$                 | $0.01705^{+0.00015}_{-0.00015}$     |
| DERIVED PARAMETERS                                     |                  |                                       |                                     |
| Semimajor axis ( $a$ )                                 | [au]             | –                                     | $0.1303^{+0.0013}_{-0.0013}$        |
| Scaled semimajor axis ( $a/R_s$ )                      | –                | –                                     | $21.54^{+0.16}_{-0.16}$             |
| Inclination ( $i$ )                                    | [deg]            | –                                     | $88.816^{+0.065}_{-0.061}$          |
| Planet Radius ( $R_p$ )                                | [ $R_\oplus$ ]   | –                                     | $2.419^{+0.027}_{-0.027}$           |
| Transit duration ( $T_{14}$ )                          | [days]           | –                                     | $0.2099^{+0.0014}_{-0.0012}$        |
| Equilibrium temperature ( $T_{eq}$ )                   | [K]              | –                                     | $970.67^{+10.54}_{-10.54}$          |
| Stellar Insolation Flux ( $S$ )                        | [ $S_\oplus$ ]   | –                                     | $148.50^{+7.12}_{-7.12}$            |
| <i>HIP 41378 c</i>                                     |                  |                                       |                                     |
| FITTED PARAMETERS                                      |                  |                                       |                                     |
| Orbital Period ( $P$ )                                 | [days]           | (fixed)                               | $31.708380^{+0.00039}_{-0.00041}$   |
| Impact Parameter ( $b$ )                               | –                | $\mathcal{U}(0, 1 + (R_\star/R_p)/2)$ | $0.9290^{+0.0041}_{-0.0044}$        |
| Planet-star radius ratio ( $R_p/R_\star$ )             | –                | $\mathcal{U}(0, 0.5)$                 | $0.01766^{+0.00043}_{-0.00042}$     |
| DERIVED PARAMETERS                                     |                  |                                       |                                     |
| Semimajor axis ( $a$ )                                 | [au]             | –                                     | $0.2093^{+0.0022}_{-0.0022}$        |
| Scaled semimajor axis ( $a/R_s$ )                      | –                | –                                     | $34.60^{+0.26}_{-0.26}$             |
| Inclination ( $i$ )                                    | [deg]            | –                                     | $88.462^{+0.015}_{-0.015}$          |
| Planet Radius ( $R_p$ )                                | [ $R_\oplus$ ]   | –                                     | $2.505^{+0.057}_{-0.056}$           |
| Transit duration ( $T_{14}$ )                          | [days]           | –                                     | $0.1212^{+0.0027}_{-0.0025}$        |
| Equilibrium temperature ( $T_{eq}$ )                   | [K]              | –                                     | $765.87^{+8.33}_{-8.33}$            |
| Stellar Insolation Flux ( $S$ )                        | [ $S_\oplus$ ]   | –                                     | $57.55^{+2.79}_{-2.79}$             |
| HOST STAR HIP 41378                                    |                  |                                       |                                     |
| Stellar density                                        | [ $\rho_\odot$ ] | $\mathcal{G}(0.5539, 0.0126)$         | $0.554^{+0.013}_{-0.013}$           |
| <i>Limb Darkening Coefficients</i>                     |                  |                                       |                                     |
| Quadratic Limb Darkening term $c_1$ ( $K2$ )           | –                | $\mathcal{G}(0.4834, 0.05)$           | $0.447^{+0.043}_{-0.043}$           |
| Quadratic Limb Darkening term $c_2$ ( $K2$ )           | –                | $\mathcal{G}(0.1535, 0.05)$           | $0.157^{+0.046}_{-0.046}$           |
| Quadratic Limb Darkening term $c_1$ (TESS)             | –                | $\mathcal{G}(0.3822, 0.05)$           | $0.401^{+0.047}_{-0.047}$           |
| Quadratic Limb Darkening term $c_2$ (TESS)             | –                | $\mathcal{G}(0.1429, 0.05)$           | $0.171^{+0.048}_{-0.048}$           |
| Quadratic Limb Darkening term $c_1$ (HST)              | –                | $\mathcal{G}(0.228, 0.05)$            | $0.183^{+0.041}_{-0.042}$           |
| Quadratic Limb Darkening term $c_2$ (HST)              | –                | $\mathcal{G}(0.1398, 0.05)$           | $0.127^{+0.046}_{-0.045}$           |
| Quadratic Limb Darkening term $c_1$ ( <i>Spitzer</i> ) | –                | $\mathcal{G}(0.0969, 0.05)$           | $0.108^{+0.049}_{-0.047}$           |
| Quadratic Limb Darkening term $c_2$ ( <i>Spitzer</i> ) | –                | $\mathcal{G}(0.0508, 0.05)$           | $0.058^{+0.049}_{-0.047}$           |
| Quadratic Limb Darkening term $c_1$ (CHEOPS)           | –                | $\mathcal{G}(0.4947, 0.05)$           | $0.463^{+0.040}_{-0.041}$           |
| Quadratic Limb Darkening term $c_2$ (CHEOPS)           | –                | $\mathcal{G}(0.1519, 0.05)$           | $0.150^{+0.045}_{-0.045}$           |

The listed best-fit values and uncertainties are the medians and 15.865th-84.135th percentiles of the posterior distributions, respectively.

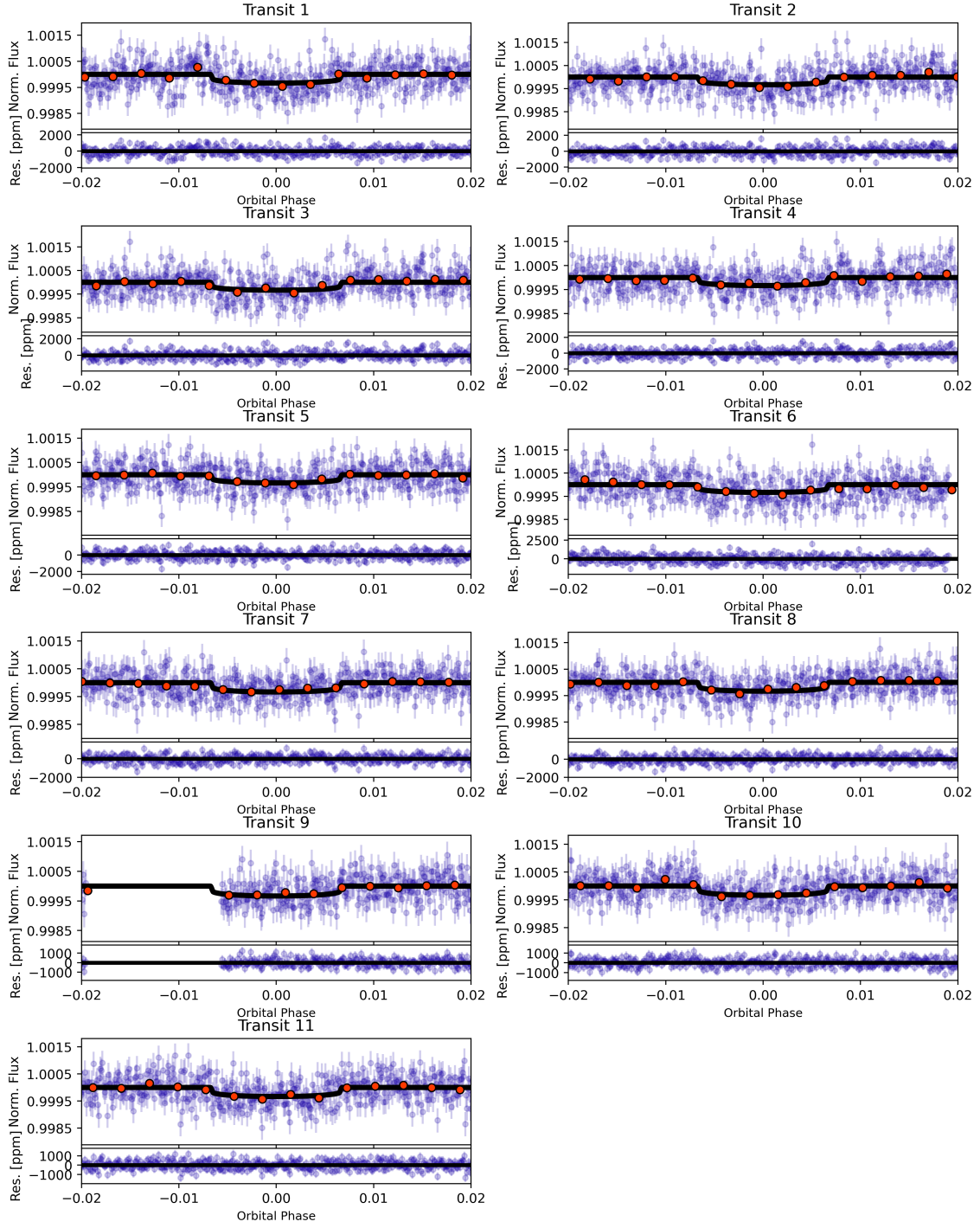


Figure 3.7: Individual TESS phase-folded transit light-curves of HIP 41378 b. The binned points are showed in red. The oversampled best-fit transit models are overlaid on the light curves.

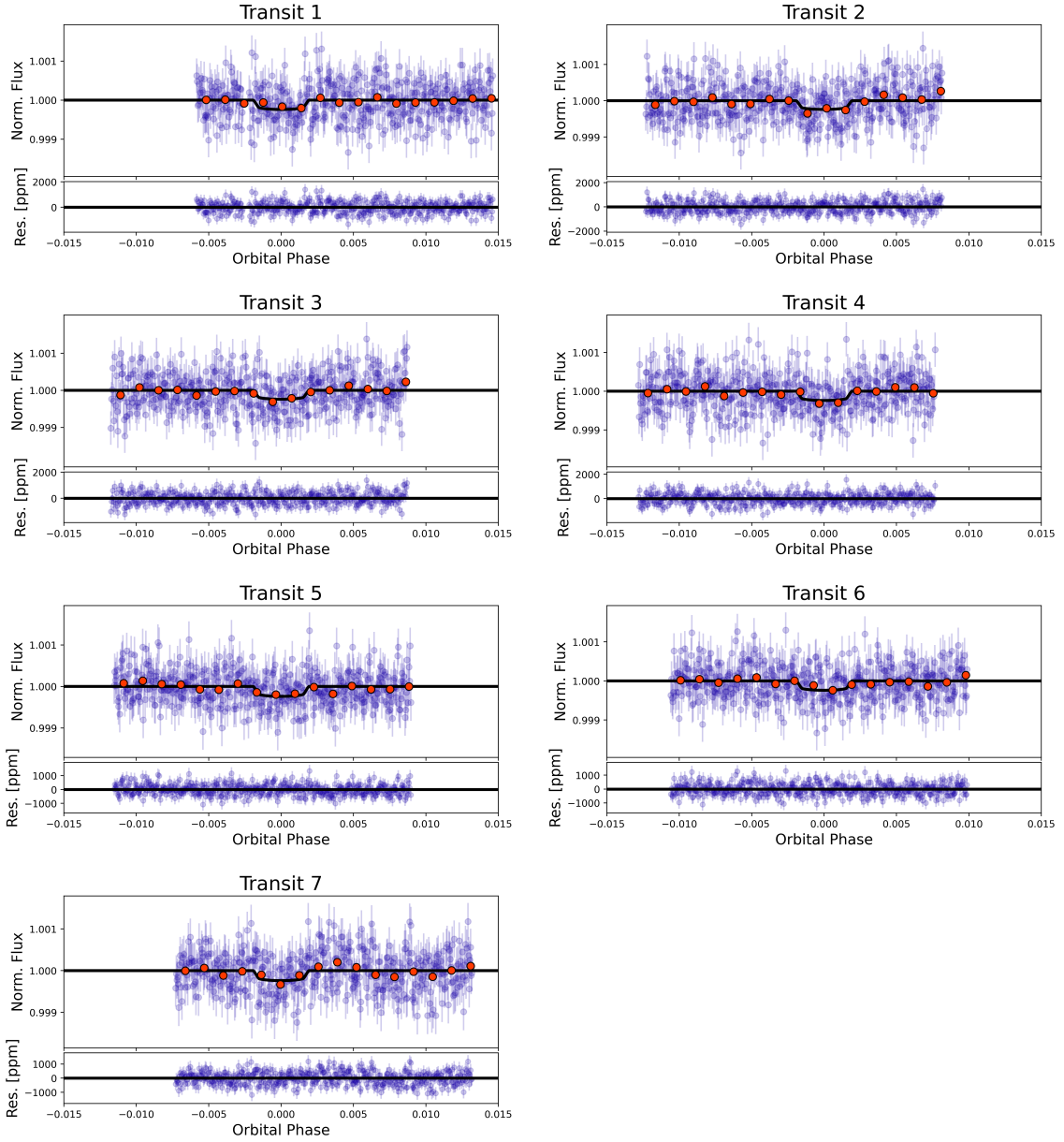


Figure 3.8: Individual TESS phase-folded transit light-curves of HIP 41378 c. The binned points are showed in red. The oversampled best-fit transit models are overlaid on the light curves.

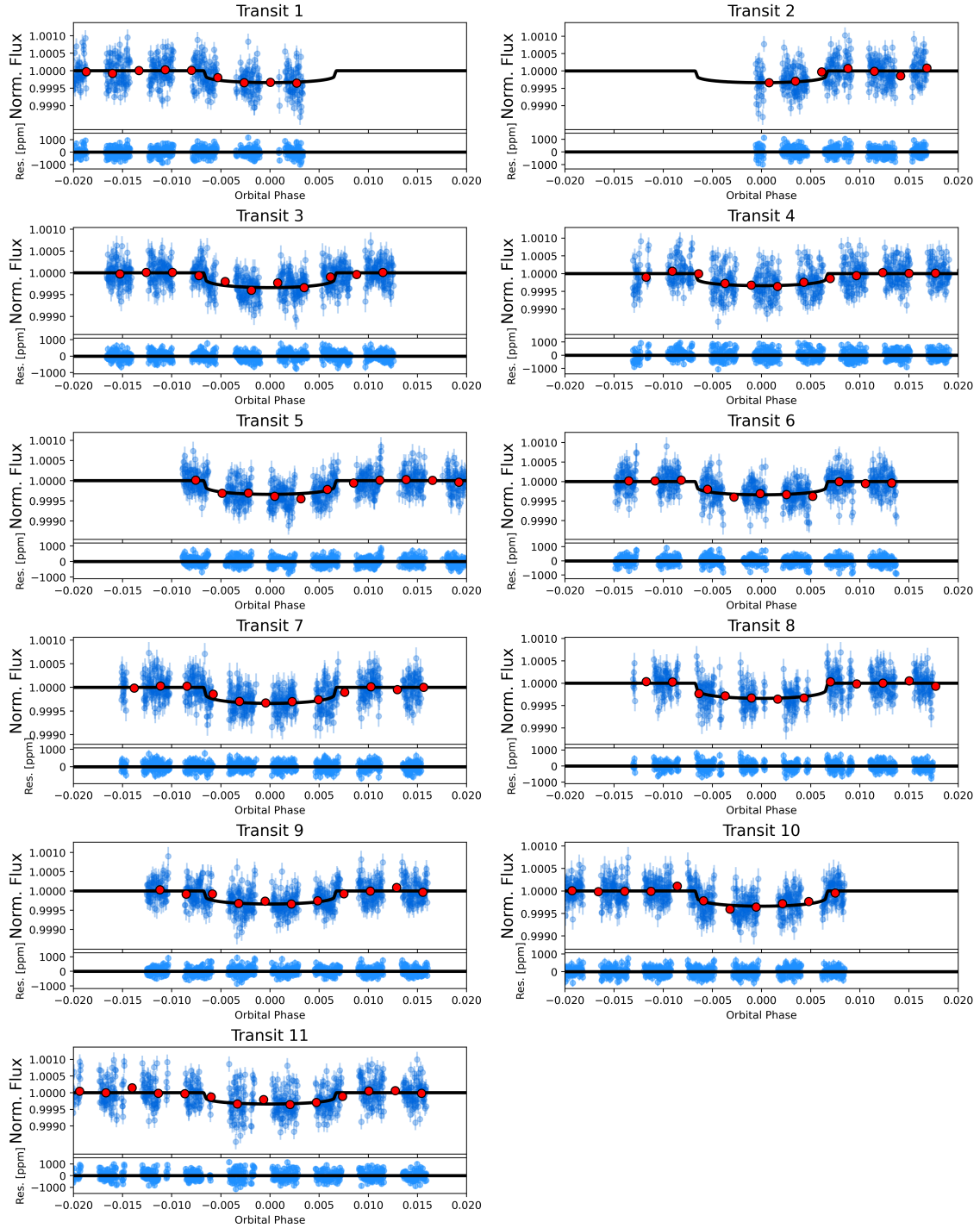


Figure 3.9: Individual CHEOPS phase-folded transit light-curves of HIP 41378 b. The binned points are showed in red. The oversampled best-fit transit models are overlaid on the light curves.

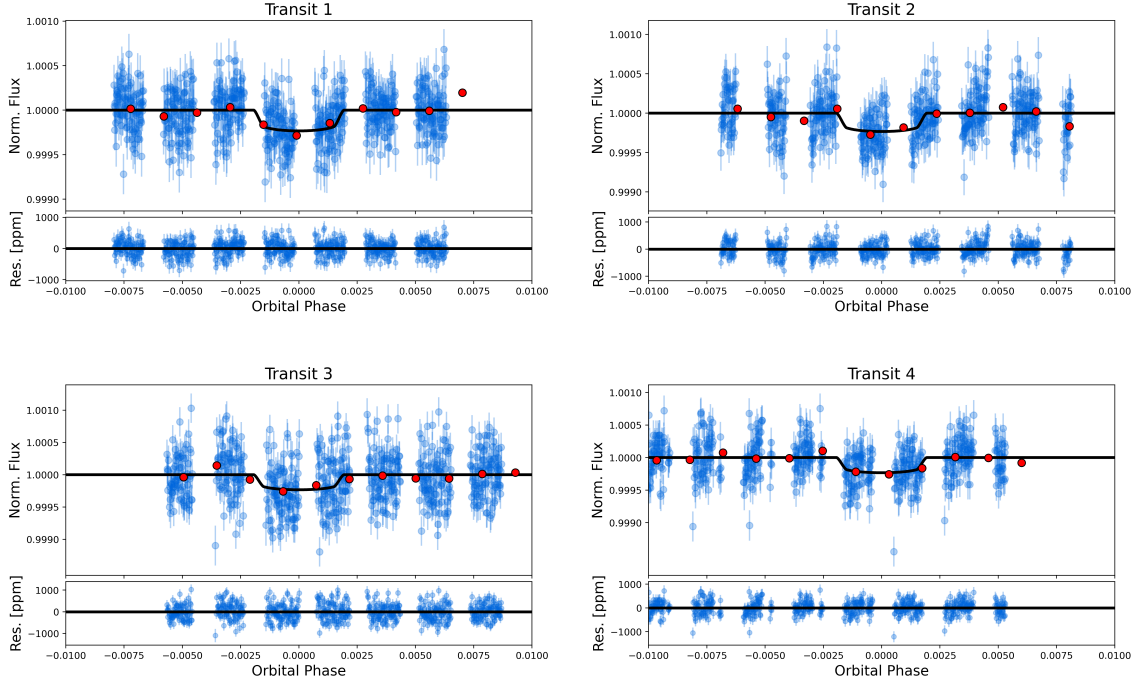


Figure 3.10: Individual CHEOPS phase-folded transit light-curves of HIP 41378 c. The binned points are showed in red. The oversampled best-fit transit models are overlaid on the light curves.

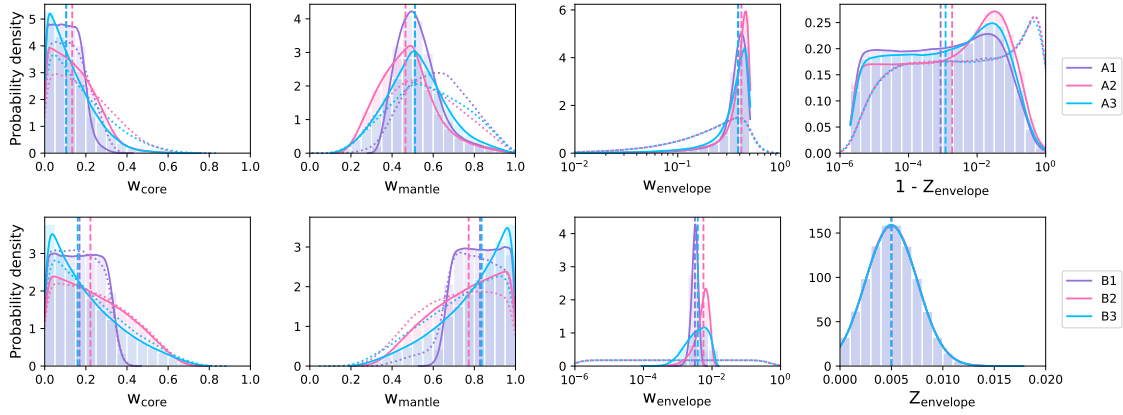


Figure 3.11: Posteriors for the main internal structure parameters of HIP 41378 b, namely the mass fractions of the planet's inner core (far left), mantle (middle left), and envelope layers (middle right), as well as the mass fraction of water in the envelope layer (far right). We show models assuming the planet's Si/Mg/Fe ratios to match the ones of the host star exactly (purple), to be Fe-enriched compared to the host star (pink), and to be independent from the host star metallicity (blue). For all three options, we also use two water priors, favoring a water-rich (top row) and water-poor composition (bottom row), respectively. The dashed vertical lines show the medians of the inferred distributions, the dotted lines the chosen priors.

Table 3.6: Posteriors and derived orbital parameters (MAP and HDI) for HIP 41378 b, c, and g obtained from the dynamical analysis with TRADES.

| Parameter                                           | Unit                                         | Prior                                  | MAP (HDI $\pm 1\sigma$ )            |
|-----------------------------------------------------|----------------------------------------------|----------------------------------------|-------------------------------------|
| <i>HIP 41378 b</i>                                  |                                              |                                        |                                     |
| FITTED PARAMETERS                                   |                                              |                                        |                                     |
| $M_p/M_\star$                                       | $[(\frac{M_\odot}{M_\star}) \times 10^{-6}]$ | $\mathcal{U}(0.30, 954.7)$             | $22^{+3}_{-1}$                      |
| Orbital Period ( $P$ )                              | [days]                                       | $\mathcal{U}(13.5, 17.5)$              | $15.571306^{+0.000011}_{-0.000323}$ |
| $\sqrt{e} \cos \omega$                              | –                                            | $\mathcal{U}(-\sqrt{0.5}, \sqrt{0.5})$ | $0.142^{+0.011}_{-0.037}$           |
| $\sqrt{e} \sin \omega$                              | –                                            | $\mathcal{U}(-\sqrt{0.5}, \sqrt{0.5})$ | $-0.033^{+0.032}_{-0.038}$          |
| Mean Longitude ( $\lambda$ )                        | [deg]                                        | $\mathcal{U}(0, 360)$                  | $274.34^{+1.09}_{-0.28}$            |
| DERIVED PARAMETERS                                  |                                              |                                        |                                     |
| Mass ( $m_p$ )                                      | $[M_\oplus]$                                 | –                                      | $9.06^{+1.41}_{-0.51}$              |
| Eccentricity ( $e$ )                                | –                                            | $\mathcal{N}^+(0, 0.083)$              | $0.0213^{+0.0022}_{-0.0099}$        |
| Argument of Periastron ( $\omega$ )                 | [deg]                                        | –                                      | $-13^{+14}_{-17}$                   |
| Mean Anomaly ( $M_A$ )                              | [deg]                                        | –                                      | $107^{+16}_{-15}$                   |
| <i>HIP 41378 c</i>                                  |                                              |                                        |                                     |
| FITTED PARAMETERS                                   |                                              |                                        |                                     |
| $M_p/M_\star$                                       | $[(\frac{M_\odot}{M_\star}) \times 10^{-6}]$ | $\mathcal{U}(0.30, 954.7)$             | $16^{+3}_{-1}$                      |
| Orbital Period ( $P$ )                              | [days]                                       | $\mathcal{U}(30, 34)$                  | $31.71054^{+0.00172}_{-0.00098}$    |
| $\sqrt{e} \cos \omega$                              | –                                            | $\mathcal{U}(-\sqrt{0.5}, \sqrt{0.5})$ | $-0.242^{+0.039}_{-0.010}$          |
| $\sqrt{e} \sin \omega$                              | –                                            | $\mathcal{U}(-\sqrt{0.5}, \sqrt{0.5})$ | $0.096^{+0.054}_{-0.015}$           |
| Mean Longitude ( $\lambda$ )                        | [deg]                                        | $\mathcal{U}(0, 360)$                  | $333^{+8}_{-2}$                     |
| Longitude of Ascending Node ( $\Omega$ )            | [deg]                                        | –                                      | $173^{+9}_{-1}$                     |
| DERIVED PARAMETERS                                  |                                              |                                        |                                     |
| Mass ( $m_p$ )                                      | $[M_\oplus]$                                 | –                                      | $6.53^{+1.33}_{-0.42}$              |
| Eccentricity ( $e$ )                                | –                                            | $\mathcal{N}^+(0, 0.083)$              | $0.0678^{+0.0078}_{-0.0097}$        |
| Argument of Periastron ( $\omega$ )                 | [deg]                                        | –                                      | $158^{+4}_{-13}$                    |
| Mean Anomaly ( $M_A$ )                              | [deg]                                        | –                                      | $2^{+13}_{-3}$                      |
| <i>HIP 41378 g</i>                                  |                                              |                                        |                                     |
| FITTED PARAMETERS                                   |                                              |                                        |                                     |
| $M_p/M_\star$                                       | $[(\frac{M_\odot}{M_\star}) \times 10^{-6}]$ | $\mathcal{U}(0.30, 901)$               | $17^{+3}_{-2}$                      |
| Orbital Period ( $P$ )                              | [days]                                       | $\mathcal{U}(32, 200)$                 | $64.067^{+0.026}_{-0.067}$          |
| $\sqrt{e} \cos \omega$                              | –                                            | $\mathcal{U}(-\sqrt{0.5}, \sqrt{0.5})$ | $-0.091^{+0.073}_{-0.116}$          |
| $\sqrt{e} \sin \omega$                              | –                                            | $\mathcal{U}(-\sqrt{0.5}, \sqrt{0.5})$ | $-0.043^{+0.231}_{-0.011}$          |
| Mean Longitude ( $\lambda$ )                        | [deg]                                        | $\mathcal{U}(0, 360)$                  | $350^{+4}_{-22}$                    |
| Inclination ( $i$ )                                 | [deg]                                        | –                                      | $95^{+1}_{-10}$                     |
| Longitude of Ascending Node ( $\Omega$ )            | [deg]                                        | –                                      | $184^{+6}_{-6}$                     |
| DERIVED PARAMETERS                                  |                                              |                                        |                                     |
| Mass ( $m_p$ )                                      | $[M_\oplus]$                                 | –                                      | $6.81^{+1.14}_{-0.98}$              |
| Eccentricity ( $e$ )                                | –                                            | $\mathcal{N}^+(0, 0.083)$              | $0.010^{+0.031}_{-0.010}$           |
| Argument of Periastron ( $\omega$ )                 | [deg]                                        | –                                      | $205^{+5}_{-115}$                   |
| Mean Anomaly ( $M_A$ )                              | [deg]                                        | –                                      | $-39^{+117}_{-8}$                   |
| ADDITIONAL PARAMETERS                               |                                              |                                        |                                     |
| Radial Velocity Jitter ( $\sigma_{\text{jitter}}$ ) | [m/s]                                        | –                                      | $2.36^{+0.19}_{-0.10}$              |
| Radial Velocity offset ( $\gamma_1$ )               | [m/s]                                        | –                                      | $50711.789^{+0.095}_{-0.241}$       |

The symbols  $\mathcal{U}$ ,  $\mathcal{G}$ , and  $\mathcal{N}^+$  refer to uniform, Gaussian, and half-Gaussian distributions, respectively.

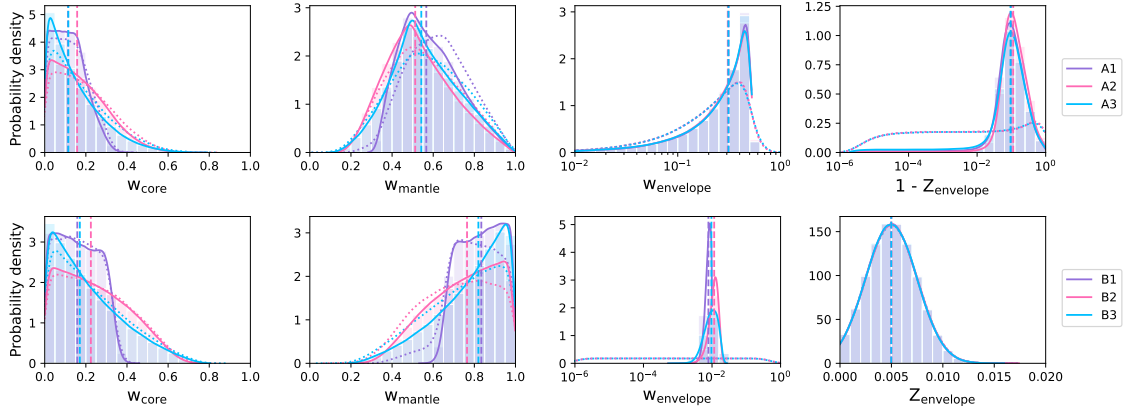


Figure 3.12: Same as Figure 3.11 but for HIP 41378 c.

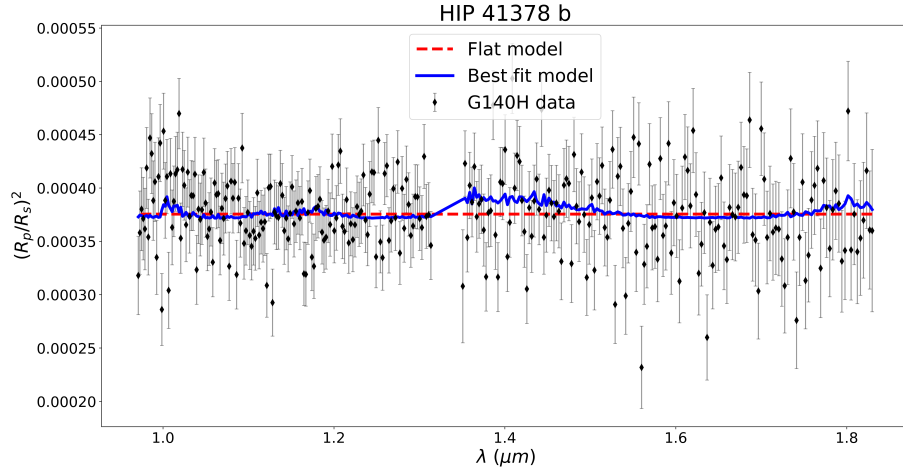
Table 3.7: Results of the internal structure modelling for HIP 41378 b.

| Water prior                | Formation outside iceline (water-rich) |                       |                       | Formation inside iceline (water-poor) |                        |                        |
|----------------------------|----------------------------------------|-----------------------|-----------------------|---------------------------------------|------------------------|------------------------|
| Si/Mg/Fe prior             | Stellar (A1)                           | Iron-enriched (A2)    | Free (A3)             | Stellar (B1)                          | Iron-enriched (B2)     | Free (B3)              |
| $w_{\text{core}}$ [%]      | $10^{+7}_{-7}$                         | $13^{+12}_{-9}$       | $10^{+13}_{-8}$       | $17^{+12}_{-12}$                      | $22^{+21}_{-16}$       | $16^{+22}_{-12}$       |
| $w_{\text{mantle}}$ [%]    | $51^{+11}_{-9}$                        | $47^{+13}_{-13}$      | $51^{+15}_{-14}$      | $83^{+12}_{-12}$                      | $77^{+16}_{-21}$       | $84^{+12}_{-22}$       |
| $w_{\text{envelope}}$ [%]  | $38.9^{+6.5}_{-10.1}$                  | $41.6^{+5.8}_{-13.7}$ | $38.5^{+7.9}_{-14.8}$ | $0.32^{+0.07}_{-0.07}$                | $0.56^{+0.23}_{-0.25}$ | $0.39^{+0.38}_{-0.23}$ |
| $Z_{\text{envelope}}$ [%]  | $99.9^{+0.1}_{-3.2}$                   | $99.8^{+0.2}_{-5.2}$  | $99.9^{+0.1}_{-3.9}$  | $0.5^{+0.2}_{-0.2}$                   | $0.5^{+0.2}_{-0.2}$    | $0.5^{+0.2}_{-0.2}$    |
| $x_{\text{Fe,core}}$ [%]   | $90.3^{+6.5}_{-6.4}$                   | $90.3^{+6.5}_{-6.4}$  | $90.3^{+6.6}_{-6.3}$  | $90.3^{+6.5}_{-6.4}$                  | $90.4^{+6.5}_{-6.4}$   | $90.3^{+6.5}_{-6.4}$   |
| $x_{\text{S,core}}$ [%]    | $9.7^{+6.4}_{-6.5}$                    | $9.7^{+6.4}_{-6.5}$   | $9.7^{+6.3}_{-6.6}$   | $9.7^{+6.4}_{-6.5}$                   | $9.6^{+6.4}_{-6.5}$    | $9.7^{+6.4}_{-6.5}$    |
| $x_{\text{Si,mantle}}$ [%] | $40^{+7}_{-6}$                         | $36^{+9}_{-9}$        | $36^{+29}_{-25}$      | $40^{+7}_{-6}$                        | $35^{+10}_{-9}$        | $36^{+29}_{-24}$       |
| $x_{\text{Mg,mantle}}$ [%] | $42^{+7}_{-7}$                         | $37^{+10}_{-10}$      | $38^{+32}_{-26}$      | $42^{+7}_{-7}$                        | $37^{+10}_{-10}$       | $36^{+30}_{-25}$       |
| $x_{\text{Fe,mantle}}$ [%] | $17^{+9}_{-11}$                        | $26^{+19}_{-17}$      | $18^{+22}_{-13}$      | $17^{+9}_{-11}$                       | $27^{+19}_{-18}$       | $19^{+24}_{-14}$       |

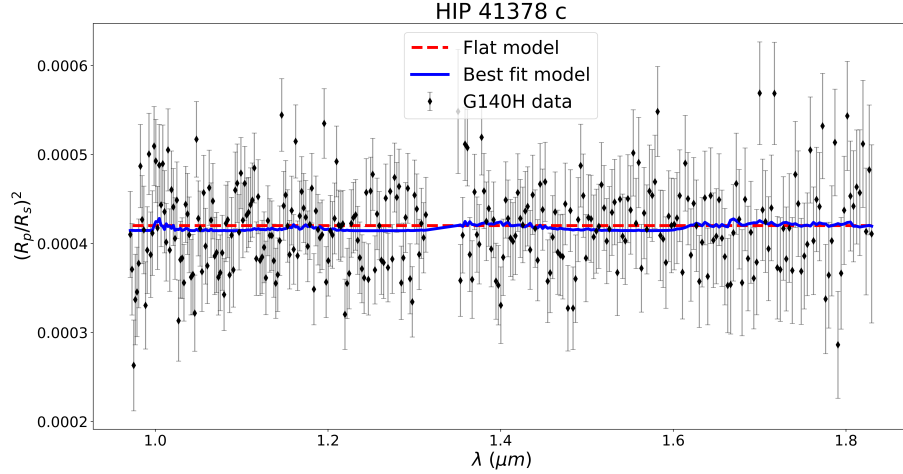
Table 3.8: Results of the internal structure modelling for HIP 41378 c.

| Water prior                | Formation outside iceline (water-rich) |                        |                        | Formation inside iceline (water-poor) |                        |                        |
|----------------------------|----------------------------------------|------------------------|------------------------|---------------------------------------|------------------------|------------------------|
| Si/Mg/Fe prior             | Stellar (A1)                           | Iron-enriched (A2)     | Free (A3)              | Stellar (B1)                          | Iron-enriched (B2)     | Free (B3)              |
| $w_{\text{core}}$ [%]      | $11^{+9}_{-8}$                         | $16^{+15}_{-11}$       | $11^{+16}_{-8}$        | $17^{+12}_{-11}$                      | $22^{+20}_{-16}$       | $17^{+22}_{-12}$       |
| $w_{\text{mantle}}$ [%]    | $57^{+17}_{-13}$                       | $51^{+19}_{-14}$       | $54^{+19}_{-14}$       | $83^{+11}_{-12}$                      | $76^{+16}_{-20}$       | $82^{+13}_{-22}$       |
| $w_{\text{envelope}}$ [%]  | $31.2^{+14.8}_{-19.2}$                 | $30.7^{+15.0}_{-18.8}$ | $31.1^{+14.7}_{-19.3}$ | $0.83^{+0.20}_{-0.19}$                | $1.16^{+0.35}_{-0.36}$ | $0.96^{+0.50}_{-0.38}$ |
| $Z_{\text{envelope}}$ [%]  | $90.4^{+5.4}_{-13.3}$                  | $88.7^{+5.8}_{-15.0}$  | $90.6^{+6.2}_{-13.4}$  | $0.5^{+0.2}_{-0.2}$                   | $0.5^{+0.2}_{-0.2}$    | $0.5^{+0.2}_{-0.2}$    |
| $x_{\text{Fe,core}}$ [%]   | $90.2^{+6.6}_{-6.3}$                   | $90.3^{+6.5}_{-6.4}$   | $90.3^{+6.6}_{-6.3}$   | $90.3^{+6.6}_{-6.4}$                  | $90.4^{+6.5}_{-6.4}$   | $90.3^{+6.5}_{-6.4}$   |
| $x_{\text{S,core}}$ [%]    | $9.8^{+6.3}_{-6.6}$                    | $9.7^{+6.4}_{-6.5}$    | $9.7^{+6.3}_{-6.6}$    | $9.7^{+6.4}_{-6.6}$                   | $9.6^{+6.4}_{-6.5}$    | $9.7^{+6.4}_{-6.5}$    |
| $x_{\text{Si,mantle}}$ [%] | $40^{+7}_{-6}$                         | $35^{+10}_{-9}$        | $32^{+31}_{-24}$       | $40^{+7}_{-6}$                        | $35^{+10}_{-9}$        | $35^{+29}_{-24}$       |
| $x_{\text{Mg,mantle}}$ [%] | $42^{+7}_{-7}$                         | $37^{+10}_{-10}$       | $40^{+36}_{-27}$       | $42^{+7}_{-7}$                        | $37^{+10}_{-10}$       | $36^{+30}_{-25}$       |
| $x_{\text{Fe,mantle}}$ [%] | $17^{+9}_{-11}$                        | $27^{+19}_{-18}$       | $18^{+24}_{-14}$       | $18^{+9}_{-11}$                       | $27^{+19}_{-18}$       | $20^{+24}_{-15}$       |





(a) Simulated observation of HIP 41378 b and retrieved best fit model for  $Z = 1 Z_{\odot}$  (blue solid line) and for a flat spectrum (red dashed line)



(b) Simulated observation of HIP 41378 c and retrieved best fit model for  $Z = 1 Z_{\odot}$  (blue solid line) and for a flat spectrum (red dashed line)

Figure 3.13: NIRSpec simulations using the g140h disperser (black points) at resolution  $R = 500$  and TauREx best fit models for HIP 41378 b and c. Both simulations adopted a solar metallicity ( $Z = Z_{\odot}$ ) atmosphere.

Table 3.9: Central times of transit for the upcoming JWST-visible observations of HIP 41378 b and HIP 41378 c in 2025 and 2026, according to the predictions of our dynamical modeling.

| Planet      | Transit Times [BJD <sub>TDB</sub> ]                                                                                                                                                                                                        |
|-------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| HIP 41378 b | 2460982.9613 ± 0.0068, 2460998.5325 ± 0.0068, 2461014.1033 ± 0.0069,<br>2461123.0990 ± 0.0067, 2461138.6698 ± 0.0066, 2461154.2406 ± 0.0065,<br>2461341.0922 ± 0.0064, 2461356.6633 ± 0.0065, 2461372.2346 ± 0.0065, 2461387.8058 ± 0.0065 |
| HIP 41378 c | 2461000.1339 ± 0.0067, 2461126.9789 ± 0.0149, 2461158.6917 ± 0.0176,<br>2461348.9791 ± 0.0300, 2461380.6945 ± 0.0313                                                                                                                       |





# 4

## **Navigating the V1298 Tau Maze: Revising Planetary Masses and Orbital Architecture of an infant system**

### **4.1 Young Planets: A puzzle still unfolding**

One of the most fundamental questions in exoplanetary science concerns the formation and early evolution of planetary systems. The detection and characterization of young exoplanets provide a rare opportunity to directly probe these early stages, offering valuable insight into the physical processes that sculpt planetary architectures. Despite the discovery of nearly 6 000 exoplanets, the mechanisms governing their physical and orbital evolution, particularly within the first billion years, remain poorly constrained. The first few tens of millions of years are especially critical, as planets undergo rapid structural and dynamical transformations that shape their final configurations. During this phase, processes such as thermal contraction (Lopez et al. 2012), atmospheric mass loss (Owen & Wu 2013, 2017), and orbital migration (Ida & Lin 2004; Lee et al. 2014; Lambrechts et al. 2019, e.g.) play dominant roles, driving the diversity of planetary radii, compositions, and orbital architectures observed today.

Accurate and precise estimates of planetary radii and masses, and therefore their bulk densities, are fundamental to understanding the physical mechanisms that govern planetary formation and evolution. When combined with well-determined stellar properties (e.g. ages, metallicities, and incident fluxes) and internal structure models, these bulk densities can be used to infer core compositions and the mass of primordial atmospheres (Fortney et al. 2007; Lopez & Fortney 2014). Such constraints are crucial for testing competing theories of atmospheric mass loss (Kulow et al. 2014; Oklopčić & Hirata 2018) and for evaluating the timescales of key evolutionary processes, including photo-evaporation

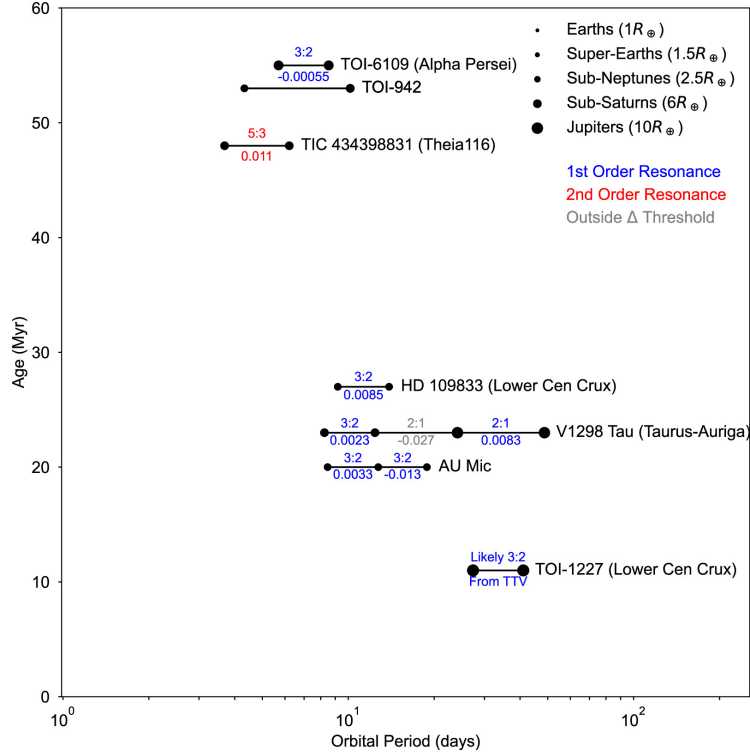


Figure 4.1: Young ( $< 100$  Myr) multi-planet systems. The period commensurabilities and the normalized distances to resonance ( $\Delta$ ) between adjacent planets are shown, with colors indicating the resonance order. Image credit: Dai et al. (2024).

(Owen & Wu 2017) and core-powered mass loss (e.g. Ginzburg et al. 2018; Gupta & Schlichting 2019). Moreover, precise mass determinations, with uncertainties better than  $\sim 5\sigma$ , are required to break degeneracies between atmospheric composition and mean molecular weight, a critical step for interpreting transmission spectra from JWST and future facilities (e.g. Batalha et al. 2019; Crossfield et al. 2025). For instance, planets with similar bulk densities may either possess water-rich interiors or hydrogen–helium envelopes; however, at young ages, planetary radii still retain distinct compositional signatures, with gas-rich sub-Neptunes appearing more inflated than water-rich counterparts, allowing their internal structures to be more readily distinguished (Rogers 2025).

Since its launch, TESS (Ricker et al. 2015) has surveyed approximately 95% of the sky, enabling the identification of the brightest and nearest young planetary systems, which represent prime targets for detailed characterization through RV and atmospheric studies (e.g. Newton et al. 2019; Battley et al. 2020; Plavchan et al. 2020; Zhou et al. 2022; Wood et al. 2023). However, RV surveys targeting young stellar populations (e.g. Paulson et al. 2004; Sato et al. 2007; Lovis & Mayor 2007; Quinn et al. 2012; Quinn et al. 2014; Mal-lorquín et al. 2023; Damasso et al. 2024) have often struggled to detect the low-amplitude Doppler signals induced by small planets, as these are frequently dominated by stellar activity (e.g. Tran et al. 2021; Nardiello et al. 2022; Blunt et al. 2023; Mantovan et al. 2024b). Young stars typically exhibit rapid rotation and enhanced magnetic activity, leading to strong quasi-periodic variations driven by star spots, plagues, flares, and pulsations (Hartmann & Noyes 1987; Saar & Donahue 1997). These phenomena can produce RV fluctuations of several  $\text{m s}^{-1}$ , often mimicking or obscuring planetary signals, thus com-

plicating the extraction of true Doppler shifts. To overcome these limitations and probe the architectures of young multi-planet systems, TTVs offer a powerful complementary approach. Interestingly, many young systems show planets in or near mean-motion resonances, where mutual gravitational interactions enhance timing signals (see Sect. 1.3). By measuring minute deviations from strictly periodic transits, TTV analyses enable the determination of planetary masses, orbital periods, and eccentricities even when stellar activity prevents precise RV measurements. When combined, the TTV and RV techniques provide a self-consistent dynamical picture of a planetary system, allowing one to break the degeneracies between mass and eccentricity, validate planetary signals, and robustly constrain the complex dynamical architectures of these systems. However, fully exploiting this synergy requires an accurate treatment of stellar activity, which remains one of the main challenges in the precise characterization of young planetary systems.

## 4.2 Dealing with Stellar Activity in Young Stars

Planetary signals in photometric and spectroscopic data may be masked or distorted by complex, time-varying noise induced by the high levels of stellar activity characteristic of young stars. Active regions, stellar areas driven by magnetic activity, host phenomena such as spots, plages, and faculae, which are modulated by stellar rotation and produce quasi-periodic signatures that overlap with the timescales of planetary orbits. In addition, stellar oscillations and surface convection processes such as granulation contribute further variability on shorter timescales. Understanding and mitigating these stellar noise sources is therefore essential to extract reliable planetary parameters and to study the early stages of planet formation and evolution.

### 4.2.1 Stellar Noise in Radial Velocities

In the RV signal of young active stars, these stellar phenomena can reach several tens to hundreds of  $\text{m s}^{-1}$ , completely overshadowing planetary signals that are typically on the order of a few  $\text{m s}^{-1}$ , and can be broadly classified according to their characteristic timescales and physical origins:

- **Short-term (minutes): Acoustic oscillations and granulation**  
As in older stars, pressure (p-mode) oscillations and granulation contribute to short-term RV noise. In young stars, however, these signals can be enhanced due to stronger convective velocities and more turbulent photospheric motions. In solar-type stars, they occur on timescales of a few minutes and induce RV variations with amplitudes of the order of  $0.5\text{--}2 \text{ m s}^{-1}$ .
- **Intermediate-term (days): Magnetic activity and surface inhomogeneities**  
Photospheric inhomogeneities, such as starspots and faculae, distort the symmetry of the spectral lines as the star rotates. The changing variability of active regions modulates the RV signal with the stellar rotation period and its harmonics, producing quasi-periodic variations that can reach tens or even hundreds of  $\text{m s}^{-1}$ . Young stars, characterized by rapid rotation ( $P_{\text{rot}} \sim 1\text{--}10$  days) and large spot coverage, often display non-stationary activity patterns, making the induced RV variability highly complex and difficult to model with simple sinusoids.

- **Long-term (months to years): Magnetic cycles**

On longer timescales, variations in the global magnetic field produce activity cycles analogous to the solar 11-year cycle. These cycles modulate the average coverage and contrast of active regions, leading to slow RV drifts over months to years.

Mitigation strategies typically combine both observational and statistical approaches. From the observational perspective, adopting exposure times longer than the characteristic oscillation period (10–15 minutes for solar-type stars) helps to average out the high-frequency variations induced by p-modes. In addition, continuous monitoring of standard activity indicators (e.g. BIS, FWHM,  $\log R'_{\text{HK}}$ ,  $\text{H}\alpha$ ) provides diagnostics of line-profile variations and magnetic activity levels. Simultaneous photometric or spectropolarimetric observations (e.g. Donati et al. 2020; Moutou et al. 2024) further constrain the evolution of active regions and the magnetic field topology, enabling a more accurate separation between stellar activity and planetary signals.

In recent years, it has become common to adopt flexible noise frameworks such as Gaussian Process (GP) regression to account for the correlated noise induced by stellar activity. The hyperparameters of the GP can be trained either on ancillary activity indicators (Haywood et al. 2014; Rajpaul et al. 2015) or directly on the RV time series (Faria et al. 2016). Among the available kernels, the quasi-periodic covariance function has proven particularly effective, as it captures both the rotational modulation and the temporal evolution of active regions through characteristic timescales linked to the stellar rotation period and spot lifetimes.

#### 4.2.2 Stellar Noise in Photometry

Photometric light-curves of young stars are dominated by variability caused by stellar activity. Large, evolving spots and faculae on the stellar surface can produce quasi-periodic brightness modulations with amplitudes of several percent, orders of magnitude larger than typical planetary transit depths.

- **Rotational modulation:** The rotation of spotted surfaces produces periodic flux variations. The evolving distribution of active regions leads to changes in amplitude and phase over time, complicating transit normalization and transit timing analysis.
- **Flares:** Flare events, common in young stars, can produce sharp flux increases that distort the light curve and bias measurements of transit depth and timing.
- **Spot-crossing events:** When a planet transits across a dark spot or bright facula, the local stellar flux changes, producing anomalies in the transit profile that can mimic transit timing variations or bias radius estimates.

Mitigating the effects of stellar activity in photometric data requires long-baseline, high-precision observations and careful detrending to preserve the planetary signal. Common techniques include basis-spline (B-spline) fitting, local polynomial regression, and GP modeling, which are used to capture the rotational modulation and instrumental systematics while isolating the transit features.

### 4.3 A progenitor of compact multi-planetary systems

Despite significant advances in recent years, the sample of known young multi-planet systems remains relatively small ( $< 10$ ), limiting our ability to conduct robust statistical studies (see Fig. 4.1). To date, only a handful of multi-planets younger than  $\sim 100$  Myr have both measured radii and masses, and even fewer belong to confirmed multi-planet systems. Among these rare systems, V1298 Tau (Age:  $20 \pm 10$  Myr,  $V = 10.12$ ) stands out as one of the most compelling benchmarks for studying early-stage planetary evolution. It hosts at least four transiting planets (David et al. 2019), making it a unique target for probing the processes shaping system architectures shortly after disk dispersal. Originally discovered with K2 (David et al. 2019) and later re-observed by TESS (Feinstein et al. 2022), the system’s photometry enabled precise period measurements for the three inner planets ( $P_c \simeq 8$  days,  $P_d \simeq 12$  days, and  $P_b \simeq 24$  days). These observations also facilitated in-transit RV and spectroscopic measurements, which were used to assess spin-orbit alignment and stellar-driven atmospheric loss (Poppenhaeger et al. 2021; Vissapragada et al. 2021; Maggio et al. 2023). However, RV-based mass measurements of these planets are severely hampered by the host star’s magnetic activity. The young star rotates rapidly, driving strong spot modulation, flares, and pulsations (Hartmann & Noyes 1987; Saar & Donahue 1997), which introduce RV jitter often comparable to or exceeding the planetary signals (Brems et al. 2019; Blunt et al. 2023). Initial RV analyses (Suárez Mascareño et al. 2021) suggested Jovian masses ( $200\text{--}400 M_{\oplus}$ ) for planets b and e, and upper limits of  $70\text{--}100 M_{\oplus}$  for c and d. These results were later challenged by follow-up observations: Finocietty et al. (2023) constrained masses of planets c and d to  $< 50 M_{\oplus}$  and planet b to  $< 150 M_{\oplus}$ ; Sikora et al. (2023) reported  $20 \pm 10 M_{\oplus}$  for c and similar upper limits for d and b. Atmospheric retrievals with HST (Barat et al. 2024) also placed the masses of planets b and c below  $20 M_{\oplus}$ , consistent with the findings of Karalis et al. (2024), who showed that most planets younger than 100 Myr tend to be low-mass and puffed-up. These results support the interpretation of the V1298 Tau system as a progenitor of compact systems of sub-Neptunes and super-Earths, potentially offering insight into formation and migration processes just after disk dispersal (Izidoro et al. 2017,  $\sim 5$  Myr;). However, with only two transits (in K2 and TESS), and a very large time gap between them, there was ambiguity about the actual orbital period of the outermost planet V1298 Tau e, with 17 possible period aliases, ranging from 44.1 to 62.8 days (Feinstein et al. 2022; Sikora et al. 2023). Through an intensive space- and ground-based photometric follow-up, carried out in collaboration with the results presented in Livingston et al. (submitted), we were able to confirm the orbital period to be  $\sim 48.68$  days, placing the planet close to a 2:1 resonance with V1298 Tau b. Notably, the three inner planets also exhibit near-resonant period ratios:  $P_c/P_d = 1.5052$  (close to 3:2) and  $P_b/P_d = 1.9464$  (close to 2:1), suggesting that the system may form part of an extended resonant chain.

To investigate this further, we analyzed a seven-year baseline of transits of the system, incorporating new ground- and space-based photometry from multiple programs, such as: NEOSat GO Cycle 7 (PI: Mann), CHEOPS GO programs PR220010 and PR230032 (PI: Damasso), and PR240005 and PR450029 (PI: Leonardi). These observations revealed clear transit timing variations (TTVs) in all four planets of the system, consistent with strong mutual gravitational interactions (see Fig. 4.2). However, the current datasets lacks sufficient transits to fully map the TTV phases and robustly constrain planetary masses,

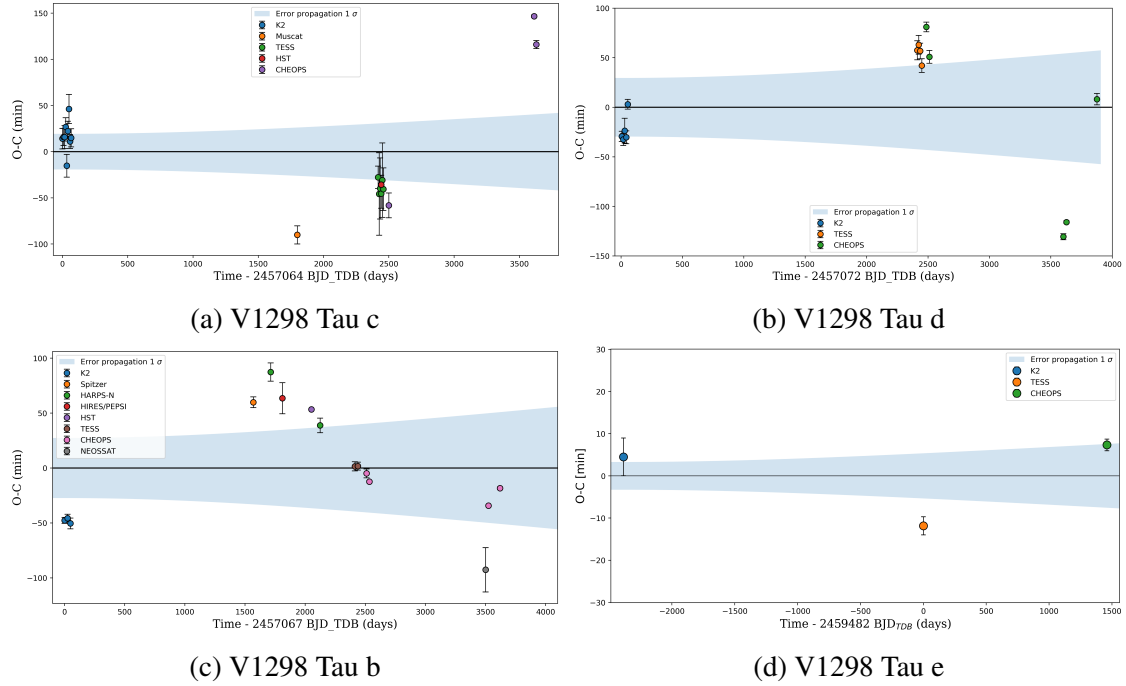


Figure 4.2: Observed-minus-calculated (O–C) diagrams for the four transiting planets of V1298 Tau. Each panel shows the transit timing residuals (in minutes) as a function of time, with error bars indicating the measurement uncertainties. Deviations from the linear ephemeris reveal the presence of planet–planet gravitational interactions and the dynamical coupling among the planets.

breaking the Mass-eccentricity degeneracy (Lithwick et al. 2012). Continued photometric monitoring, through ongoing and future observing campaigns, will be essential to improve the temporal sampling of the TTV signals, refine the planetary mass estimates, and gain deeper insight into the dynamical architecture of this young and highly interactive system.

In addition to the timing measurements, the system has been intensively monitored as part of the Global Architecture of Planetary Systems (GAPS) Young Objects (YO) long-term program with the HARPS-N and GIANO spectrographs at the TNG telescope (Carleo et al. 2021; Nardiello et al. 2022; Mantovan et al. 2024a; Damasso et al. 2024). Between 2019 and 2023, the GAPS collaboration collected nearly 400 HARPS-N spectra of the young pre-main-sequence K1 star.

Due to the strong stellar activity typical of young stars, the HARPS-N radial velocities exhibit extremely large scatter, with a semi-amplitude of  $\sim 600 \text{ m s}^{-1}$  (see Fig. 4.4). To mitigate activity-induced distortions in the CCF, I implemented a Skew-Normal (SN) fit to the cross-correlation function, following the methods developed by Simola et al. (2019) and Bonfanti et al. (2023). Traditional approaches fit the CCF with a Gaussian profile to estimate the RV and full width at half maximum (FWHM), while asymmetries are quantified separately using indicators such as the bisector span (BIS SPAN). The SN model, however, introduces a skewness parameter ( $\alpha$ ), enabling RV, FWHM, and asymmetry to be derived simultaneously in a single, self-consistent fit. The function naturally reduces to the Gaussian form for  $\alpha = 0$  (see Fig. 4.3). As demonstrated by Simola et al. (2019), this method provides improved sensitivity to subtle asymmetries in

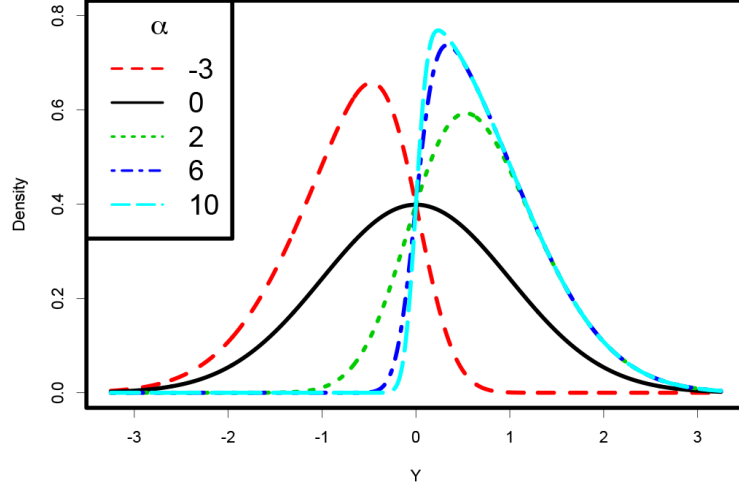


Figure 4.3: Example of the Density function with different values of the Skewness parameter  $\alpha$  indicated by different colors and line types. The solid black curve corresponds to  $\alpha = 0$ , representing the symmetric Normal distribution. Image credits: (Simola et al. 2019)

the CCF, often associated with stellar activity, and enhances the precision of RV extraction compared to standard Gaussian fits or BIS-based diagnostics.

This approach is particularly effective for magnetically active stars such as V1298 Tau, where stellar variability dominates the RV signal. To further refine the RV time series, I applied a break-point detrending technique based on ancillary activity indicators, as described by Simola et al. (2022). Given the variability of stellar activity over long observational campaigns, this method divides the RV time series into segments based on changes in the correlation between RVs and activity indicators. By applying localized corrections within each segment rather than a single global correction, this approach provides a more accurate removal of activity-induced noise across extended datasets. Together, these techniques enable the robust extraction of RV signals in the presence of strong stellar activity, improving the detectability of planetary signals and advancing our understanding of activity–RV correlations in young, active stars.

## 4.4 Future Developments: A Photodynamical Approach

Given the intrinsic limitations of RV-only analyses for young, active, and rapidly rotating stars like V1298 Tau, the precision of the derived planetary masses is fundamentally limited by activity-induced line-profile variations and non-stationary systematics. A coherent strategy is to combine all available time-domain constraints in a single, self-consistent framework, namely, a *photodynamical* model, thereby exploiting the full information content of the light curves (i.e. shapes and timings), the TTV signal, and the RVs simultaneously (Ragozzine & Holman 2010; Hadden & Lithwick 2017; Leleu et al. 2024, e.g.). A photodynamical analysis integrates the  $N$ -body equations of motion for the planetary system to predict, at each observation time, (i) the sky-projected geometry, (ii) the instantaneous transit configuration (contact times, impact parameters), and (iii) the stellar reflex velocity. From this state vector, it generates: (i) model light curves,



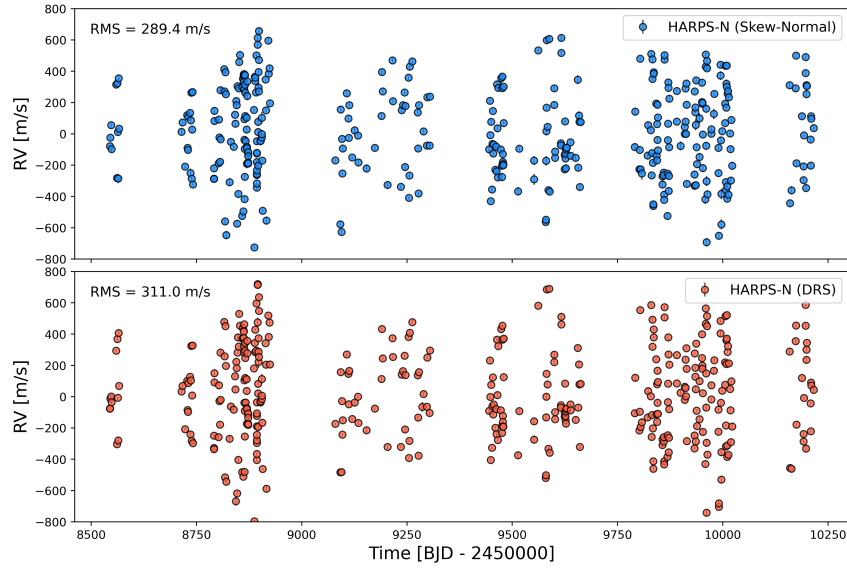


Figure 4.4: Comparison between the radial velocities of V1298 Tau extracted from HARPS-N spectra using two different approaches. Top: RVs obtained with the Skew-Normal (SN) method developed by (Simola et al. 2019), which simultaneously models line asymmetries in the CCF. Bottom: RVs derived from the standard HARPS-N Data Reduction Software (DRS) pipeline. The SN method provides a more consistent and precise RV time series, mitigating the effects of stellar activity.

accounting for limb darkening, finite exposure integration, dilution, and (optionally) spot-crossing masks; (ii) model transit times and durations via the full dynamics (including chopping and secular terms); and (iii) model RVs including the star’s barycentric reflex motion. The model is then *jointly* fit to the photometry, transit times, and RVs, optionally augmented with GP regression for stellar activity.

We will perform a joint fit of space-based photometry (*K2*, *TESS*, *CHEOPS*), ground-based light curves, and high-precision RVs (HARPS-N) within a Bayesian photodynamical framework. In this approach, the *N*-body integration self-consistently reproduces the observed light curves, TTVs, and RVs, providing direct constraints on planetary masses, eccentricities, and mutual inclinations while maintaining dynamical stability. To account for stellar activity, we will include GP components trained either on the RVs or on ancillary activity indicators (e.g. BIS, FWHM,  $H\alpha$ ,  $\log R'_{HK}$ ). A quasi-periodic GP kernel will model the correlated noise associated with stellar rotation and evolving active regions, with hyperparameters representing the amplitude, rotation period, and active-region lifetime (Haywood et al. 2014; Rajpaul et al. 2015; Faria et al. 2016, e.g.). For the photometric datasets, similar GP terms will be applied to capture rotational modulation and instrumental systematics, using independent white-noise components for each instrument. This unified approach will therefore combine dynamical modeling and statistical noise treatment, enabling robust mass and orbital determinations despite the strong activity of V1298 Tau.

# 5

## Conclusions

In this thesis, I have investigated how transit-timing and radial-velocity analyses can be used to constrain the dynamical architectures of exoplanetary systems. I have shown that decade-long observational campaigns enable the detection of subtle, long-term timing effects in hot Jupiter systems, providing new constraints on their orbital evolution and internal structures. Furthermore, I have demonstrated how the combined analysis of transit-timing and radial-velocity data can confirm the presence of non-transiting planets whose orbital periods lie close to mean-motion resonances, revealing the full dynamical architecture of their host systems. Finally, I have focused on young and active stars, where the combination of complementary techniques could allow the measurement of planetary masses and orbital parameters that would otherwise remain inaccessible, offering new insights into the early dynamical evolution of planetary systems.

In the following, I summarize the main findings of this work and outline potential directions for future research.

### 5.1 Summary

In Chap 2, I investigated the tidal orbital decay of the ultra-hot Jupiter WASP-12b. Using 28 previously unpublished ground-based light curves from the TASTE program, spanning 12 years from 2010 to 2022, I employed a DE-MCMC approach to analyze the transit time variations (TTVs) of the planet. My analysis provided robust confirmation of WASP-12b’s decaying orbit and yielded refined planetary and transit parameters consistent with prior findings. However, discrepancies in the O-C diagram, observed when combining literature data with our measurements, raise questions about WASP-12 stellar activity. To explore the origin of the extreme tidal dissipation observed, I utilized archival HARPS-N spectra to examine the host star’s evolutionary stage, a critical factor influencing tidal dissipation rates. The analysis provided precise stellar parameters, placing the star near the

main-sequence turn-off point and away from the subgiant branch. However, the high tidal dissipation rate observed in the system suggests a subgiant scenario, creating a discrepancy that remains unresolved. This work represents a significant step toward understanding the mechanisms driving tidal orbital decay. By linking precise transit timing measurements to stellar and planetary properties, my research contributes to a broader effort to refine models of tidal interactions and planetary dynamical evolution.

In Chapter 3, I investigate HIP 41378, a multi-planet system hosting five transiting planets, I performed a joint dynamical modelling of the TTV and RV signals of the two inner sub-Neptunes using extensive photometric follow-up from CHEOPS, TESS, K2, Spitzer, HST, and high-precision RVs from HARPS ). This analysis dynamically confirmed the planetary nature of HIP 41378 g, a non-transiting planet with a period of  $\sim 64$  days and a mass of about  $7 M_{\oplus}$ , located near a 2:1 commensurability with planet c, suggesting a possible mean-motion resonance chain. The precise measurement of masses, eccentricities, and radii for the inner planets allowed to investigate the possible volatile-rich compositions and offered insights into the evolutionary histories of their primordial atmospheres. Additionally, we identified the two inner planets as excellent candidates for atmospheric characterization with the NIRSpec/g140m instrument aboard JWST, to confirm the presence of a possible primordial atmosphere.

In Chapter 4, I focused on the V1298 Tau multi-planet system. I employed a Skew-Normal fitting approach to model the cross-CCF and mitigate activity-induced RV variations in nearly 400 HARPS-N spectra of this young pre-main-sequence K1 star (age  $20 \pm 10$  Myr), collected as part of the GAPS programme. Given the intrinsic limitations of RV-only analyses for young, active, and rapidly rotating stars, the precision of the derived planetary masses remains limited. To overcome this, I am combining these extracted RVs with ground- and space-based photometry, including data from the NEOSat GO Program Cycle 7, CHEOPS GO 0033 (PI: Leonardi), and CHEOPS DP 0029 (PI: Leonardi), to perform a full photodynamical characterization of the system (Leonardi et al., in prep.). Our follow-up observations have already revealed significant transit-timing variations among the outer planets, indicative of mutual gravitational interactions within the system. This combined analysis will provide more robust constraints on planetary masses, eccentricities, and orbital architecture, offering key insights into the dynamical evolution of one of the youngest known multi-planet systems.

## 5.2 Future prospects

Over the course of my PhD, I have developed and applied techniques that combine high-precision photometry, radial velocities, and dynamical modeling to study the architectures of planetary systems. Building on this experience, I now aim to broaden this work toward a more comprehensive understanding of the interior composition of eccentric HJs and on the planetary evolution in the first few hundred million years. The sample of young planets is steadily growing thanks to missions such as TESS and CHEOPS, but much remains to be understood about their internal structures, migration histories, and dynamical interactions. In the following sections, I outline two directions that I intend to pursue: the characterization of eccentric hot Jupiters through apsidal precession, and the dynamical mass determination of young sub-Neptunes and Neptunes through TTVs.

### 5.2.1 OrbitalWALTZ: Looking for Precession in Eccentric Hot Jupiters

As part of the CHEOPS Guaranteed Time of Observation (GTO), I am leading program PR150089, which focuses on the photometric follow-up of a selected sample of eccentric hot Jupiters in order to extend their observational baselines. The primary goal is to improve constraints on their orbital parameters and to search for long-term transit timing variations (TTVs) indicative of apsidal precession. Detecting and characterizing such precession not only provides key insights into the dynamical evolution of these systems, but also enables constraints on the internal structure of eccentric hot Jupiters through the determination of their planetary Love number,  $k_{2,p}$ .

The TESS mission is providing new additions to the hot Jupiter population (Yee et al. 2022; Saunders et al. 2022). Simulations from Yee et al. (2021) shows how TESS will help to increase the sample size of nearby HJs around FGK stars brighter than  $G = 12.5$  to  $\approx 400$ . Unfortunately, many of these planets have only a few years of observational baseline and, due to TESS observing strategy, the majority of observations will be clustered around intervals of one year. This makes it challenging to distinguish between long-term timing effects, such as orbital decay or apsidal precession, and short-term noise. Therefore, by extending the observational baseline with CHEOPS, we can effectively fill these gaps and enhance our sensitivity to subtle precession signals. The gradual divergence of the O-C curves over time, especially in systems with significant eccentricities, will provide a robust signal of apsidal precession. CHEOPS, with its ability to deliver high-precision photometry, is ideally suited to detect the small, long-term transit timing variations caused by apsidal precession. These variations manifest over timescales of years, particularly for hot Jupiters with eccentric orbits.

As noted by Bernabò et al. (2024), the current sample of measured Love numbers for exoplanets remains too small to draw general conclusions about planetary interiors. With our proposal, we aim to double the sample of planetary  $k_{2,p}$  values, significantly expanding the dataset. This will allow for a more comprehensive understanding of the interior structure of hot Jupiters, enabling comparisons across different systems and offering a clearer picture of the physical processes governing these planets.

### 5.2.2 Young and Resonant: Probing the Masses of Infant Multi-Planet Systems with TTVs

Many observed sub-Neptunes and Neptunes orbiting young stars appear to be “lonely” (e.g. Vach et al. 2024). However, these apparently isolated planets may in fact have undetected companions whose gravitational influence induces measurable TTVs. Given the difficulty of deriving precise planetary masses solely from radial-velocity measurements in young, active stars, TTVs provide a powerful and complementary dynamical tool for mass determination in these systems.

In the near future, I aim to perform transit follow-up observations on a statistically meaningful sample of young planetary systems, including both apparently isolated sub-Neptunes and Neptunes, as well as confirmed multi-planet systems. My goal is to refine the physical and orbital properties of these key targets and to search for TTVs that may reveal additional, unseen companions, thereby probing the dynamical architectures of young planetary systems and testing early-stage formation and migration models. TTVs

offer a valuable alternative to radial velocities, often hindered by stellar activity in young stars, for constraining planetary masses, eccentricities, and long-term stability.

By measuring planetary masses across systems spanning different evolutionary stages, I aim to trace how planets evolve in the mass–radius diagram with age, providing insights into contraction and atmospheric loss processes (e.g. Kraus et al. 2015; Maggio et al. 2022). In addition, these follow-up observations will significantly improve the precision of planetary radius estimates within my sample, a critical step toward distinguishing between gas-rich and water-rich compositions at young ages, when radius differences are most diagnostic of internal structure (e.g. Rogers 2025).

# Bibliography

- Adams, J. C. 1846, MNRAS, 7, 149
- Adibekyan, V., Dorn, C., Sousa, S. G., et al. 2021, Science, 374, 330
- Adibekyan, V., Figueira, P., Santos, N. C., et al. 2015, A&A, 583, A94
- Adibekyan, V. Z., Sousa, S. G., Santos, N. C., et al. 2012, A&A, 545, A32
- Agol, E. & Fabrycky, D. C. 2018, Transit-Timing and Duration Variations for the Discovery and Characterization of Exoplanets, ed. H. J. Deeg & J. A. Belmonte, 7
- Agol, E., Steffen, J., Sari, R., & Clarkson, W. 2005, MNRAS, 359, 567
- Aguichine, A., Mousis, O., Deleuil, M., & Marcq, E. 2021, ApJ, 914, 84
- Akinsanmi, B., Santos, N. C., Faria, J. P., et al. 2020, A&A, 635, L8
- Al-Refaie, A. F., Changeat, Q., Waldmann, I. P., & Tinetti, G. 2021, The Astrophysical Journal, 917, 37
- Alam, M. K., Kirk, J., Dressing, C. D., et al. 2022, ApJL, 927, L5
- Albrecht, S., Winn, J. N., Johnson, J. A., et al. 2012, ApJ, 757, 18
- Antonetti, V. & Goodman, J. 2022, ApJ, 939, 91
- Antoniciello, G., Borsato, L., Lacedelli, G., et al. 2021, MNRAS, 505, 1567
- Badenas-Agusti, M., Günther, M. N., Daylan, T., et al. 2020, AJ, 160, 113
- Bae, J., Zhu, Z., Baruteau, C., et al. 2019, ApJL, 884, L41
- Bai, L., Gu, S., Wang, X., et al. 2022, Monthly Notices of the Royal Astronomical Society, 512, 3113
- Bailey, A. & Goodman, J. 2018, Monthly Notices of the Royal Astronomical Society, 482, 1872
- Ballard, S., Fabrycky, D., Fressin, F., et al. 2011, ApJ, 743, 200
- Baluev, R. V., Sokov, E. N., Jones, H. R. A., et al. 2019, Monthly Notices of the Royal Astronomical Society, 490, 1294

Baranne, A., Queloz, D., Mayor, M., et al. 1996, *A&AS*, 119, 373  
 Barat, S., Désert, J.-M., Vazan, A., et al. 2024, *Nature Astronomy*, 8, 899  
 Barkaoui, K., Korth, J., Gaidos, E., et al. 2025, *A&A*, 695, A281  
 Barker, A. J. 2020, *MNRAS*, 498, 2270  
 Barros, S. C. C., Akinsanmi, B., Boué, G., et al. 2022, *A&A*, 657, A52  
 Basant, R., Luque, R., Bean, J. L., et al. 2025, *ApJL*, 982, L1  
 Batalha, N. E., Lewis, T., Fortney, J. J., et al. 2019, *ApJL*, 885, L25  
 Batalha, N. M., Rowe, J. F., Bryson, S. T., et al. 2013, 204, 24  
 Battley, M. P., Pollacco, D., & Armstrong, D. J. 2020, *MNRAS*, 496, 1197  
 Bean, J. L., Raymond, S. N., & Owen, J. E. 2021, *Journal of Geophysical Research (Planets)*, 126, e06639  
 Becker, J. C., Vanderburg, A., Rodriguez, J. E., et al. 2019, *AJ*, 157, 19  
 Bell, T. J., Zhang, M., Cubillos, P. E., et al. 2019, *MNRAS*, 489, 1995  
 Benatti, S., Claudi, R., Desidera, S., et al. 2016, in *Frontier Research in Astrophysics II (FRAPWS2016)*, 69  
 Benisty, M., Bae, J., Facchini, S., et al. 2021, *ApJL*, 916, L2  
 Benz, W., Broeg, C., Fortier, A., et al. 2021, *Experimental Astronomy*, 51, 109  
 Berardo, D., Crossfield, I. J. M., Werner, M., et al. 2019, *AJ*, 157, 185  
 Bernabò, L. M., Csizmadia, S., Smith, A. M. S., et al. 2024, *A&A*, 684, A78  
 Biazzo, K., D’Orazi, V., Desidera, S., et al. 2022, *A&A*, 664, A161  
 Biazzo, K., Gratton, R., Desidera, S., et al. 2015, *A&A*, 583, A135  
 Blackwell, D. E. & Shallis, M. J. 1977, *MNRAS*, 180, 177  
 Blunt, S., Carvalho, A., David, T. J., et al. 2023, *AJ*, 166, 62  
 Boisse, I., Bouchy, F., Hébrard, G., et al. 2011, *A&A*, 528, A4  
 Bonfanti, A., Delrez, L., Hooton, M. J., et al. 2021, *A&A*, 646, A157  
 Bonfanti, A., Gandolfi, D., Egger, J. A., et al. 2023, *A&A*, 671, L8  
 Bonfanti, A., Ortolani, S., & Nascimbeni, V. 2016, *A&A*, 585, A5  
 Bonfanti, A., Ortolani, S., Piotto, G., & Nascimbeni, V. 2015, *A&A*, 575, A18  
 Bonomo, A. S., Desidera, S., Benatti, S., et al. 2017, *A&A*, 602, A107

- Borsato, L., Degen, D., Leleu, A., et al. 2024, *A&A*, 689, A52
- Borsato, L., Malavolta, L., Piotto, G., et al. 2019, *MNRAS*, 484, 3233
- Borsato, L., Marzari, F., Nascimbeni, V., et al. 2014, *A&A*, 571, A38
- Borsato, L., Nascimbeni, V., Piotto, G., & Szabó, G. 2022, *Experimental Astronomy*, 53, 635
- Borsato, L., Piotto, G., Gandolfi, D., et al. 2021, *MNRAS*, 506, 3810
- Borucki, W. J., Koch, D. G., Basri, G., et al. 2011, *ApJ*, 736, 19
- Borucki, W. J. & Summers, A. L. 1984, *Icarus*, 58, 121
- Bouchy, F., Mayor, M., Lovis, C., et al. 2009, *A&A*, 496, 527
- Bouma, L. G., Winn, J. N., Baxter, C., et al. 2019, *AJ*, 157, 217
- Brande, J., Crossfield, I. J. M., Kreidberg, L., et al. 2024, *ApJL*, 961, L23
- Brems, S. S., Kürster, M., Trifonov, T., Reffert, S., & Quirrenbach, A. 2019, *A&A*, 632, A37
- Brown-Sevilla, S. B., Nascimbeni, V., Borsato, L., et al. 2021, *MNRAS*, 506, 2122
- Bryant, E. M., Bayliss, D., Santerne, A., et al. 2021, *MNRAS*, 504, L45
- Buchner, J., Georgakakis, A., Nandra, K., et al. 2014, *A&A*, 564, A125
- Buhler, P. B., Knutson, H., Batygin, K., et al. 2016, in *American Astronomical Society Meeting Abstracts*, Vol. 227, *American Astronomical Society Meeting Abstracts #227*, 406.07
- Butler, R. P., Marcy, G. W., Williams, E., Hauser, H., & Shirts, P. 1997, 474, L115
- Cabrera, J., Csizmadia, S., Lehmann, H., et al. 2013, *The Astrophysical Journal*, 781, 18
- Campante, T. L., Barclay, T., Swift, J. J., et al. 2015, *ApJ*, 799, 170
- Carleo, I., Desidera, S., Nardiello, D., et al. 2021, *A&A*, 645, A71
- Carrera, D., Raymond, S. N., & Davies, M. B. 2019, *A&A*, 629, L7
- Castelli, F. & Kurucz, R. L. 2003a, in *Modelling of Stellar Atmospheres*, ed. N. Piskunov, W. W. Weiss, & D. F. Gray, Vol. 210, A20
- Castelli, F. & Kurucz, R. L. 2003b, in *IAU Symposium*, Vol. 210, *Modelling of Stellar Atmospheres*, ed. N. Piskunov, W. W. Weiss, & D. F. Gray, A20
- Chakrabarty, A. & Sengupta, S. 2019, *AJ*, 158, 39
- Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. 2000, 529, L45



- Chatterjee, S., Krantzler, S. O., & Ford, E. B. 2016, IAU Focus Meeting, 29A, 30
- Chen, K., Cardenas, O., Bonifacio, B., et al. 2025, *ApJ*, 982, 100
- Choi, J., Dotter, A., Conroy, C., et al. 2016, *ApJ*, 823, 102
- Cincotta, P. M., Giordano, C. M., & Simó, C. 2003, *Physica D Nonlinear Phenomena*, 182, 151
- Cincotta, P. M. & Simó, C. 2000, *A&AS*, 147, 205
- Collier Cameron, A. & Jardine, M. 2018, *MNRAS*, 476, 2542
- Collins, K. A., Kielkopf, J. F., & Stassun, K. G. 2017, 153, 78
- Cosentino, R., Lovis, C., Pepe, F., et al. 2012, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 8446, *Ground-based and Airborne Instrumentation for Astronomy IV*, ed. I. S. McLean, S. K. Ramsay, & H. Takami, 84461V
- Cosentino, R., Lovis, C., Pepe, F., et al. 2014, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 9147, *Ground-based and Airborne Instrumentation for Astronomy V*, ed. S. K. Ramsay, I. S. McLean, & H. Takami, 91478C
- Covino, E., Esposito, M., Barbieri, M., et al. 2013, *A&A*, 554, A28
- Cowan, N. B. & Agol, E. 2011, *The Astrophysical Journal*, 729, 54
- Crane, J. D., Sackett, S. A., & Butler, R. P. 2006, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 6269, *Ground-based and Airborne Instrumentation for Astronomy*, ed. I. S. McLean & M. Iye, 626931
- Crane, J. D., Sackett, S. A., Butler, R. P., et al. 2010, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 7735, *Ground-based and Airborne Instrumentation for Astronomy III*, ed. I. S. McLean, S. K. Ramsay, & H. Takami, 773553
- Crane, J. D., Sackett, S. A., Butler, R. P., Thompson, I. B., & Burley, G. S. 2008, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 7014, *Ground-based and Airborne Instrumentation for Astronomy II*, ed. I. S. McLean & M. M. Casali, 701479
- Cresswell, P. & Nelson, R. P. 2006, *A&A*, 450, 833
- Crossfield, I. J. M., Polanski, A. S., Robertson, P., et al. 2025, *The Astronomical Journal*, 169, 89
- Cubillos, P. E. 2024, *PASP*, 136, 124501
- Cumming, A., Marcy, G. W., & Butler, R. P. 1999, *The Astrophysical Journal*, 526, 890
- Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, *VizieR Online Data Catalog*, II/246

Dai, F., Goldberg, M., Batygin, K., et al. 2024, *AJ*, 168, 239

Damasso, M., Locci, D., Benatti, S., et al. 2024, *A&A*, 690, A235

David, T. J., Petigura, E. A., Luger, R., et al. 2019, *ApJL*, 885, L12

Dawson, R. I. & Johnson, J. A. 2018, *ARA&A*, 56, 175

Debrecht, A., Carroll-Nellenback, J., Frank, A., et al. 2018, *Monthly Notices of the Royal Astronomical Society*, 478, 2592

Deck, K. M. & Agol, E. 2016, *The Astrophysical Journal*, 821, 96

Deheuvelds, S., Brandão, I., Silva Aguirre, V., et al. 2016, *A&A*, 589, A93

Delisle, J. B. 2017, *A&A*, 605, A96

Delrez, L., Leleu, A., Brandeker, A., et al. 2023, *A&A*, 678, A200

Donati, J.-F., Kouach, D., Moutou, C., et al. 2020, *MNRAS*, 498, 5684

Dorn, C. & Lichtenberg, T. 2021, *ApJL*, 922, L4

Dotter, A. 2016, *ApJS*, 222, 8

Dotter, A., Chaboyer, B., Jevremović, D., et al. 2008, *ApJS*, 178, 89

Doyle, A. P., Davies, G. R., Smalley, B., Chaplin, W. J., & Elsworth, Y. 2014, *MNRAS*, 444, 3592

Dragomir, D., Kane, S. R., Pilyavsky, G., et al. 2011, *AJ*, 142, 115

Dressing, C. D. & Charbonneau, D. 2013, 767, 95

Eastman, J., Siverd, R., & Gaudi, B. S. 2010, *PASP*, 122, 935

Edwards, B., Changeat, Q., Tsiaras, A., et al. 2023a, *AJ*, 166, 158

Edwards, B., Changeat, Q., Tsiaras, A., et al. 2023b, *AJ*, 166, 158

Edwards, B., Changeat, Q., Tsiaras, A., et al. 2023, *The Astrophysical Journal Supplement Series*, 269, 31

Efroimsky, M. & Makarov, V. V. 2022, *Universe*, 8, 211

Egger, J. A., Osborn, H. P., Kubyskhina, D., et al. 2024, *A&A*, 688, A223

Eggleton, P. P., Kiseleva, L. G., & Hut, P. 1998, *ApJ*, 499, 853

Emsenhuber, A., Mordasini, C., Burn, R., et al. 2021, *A&A*, 656, A70

Esteves, L., Izidoro, A., Winter, O. C., Bitsch, B., & Isella, A. 2023, *MNRAS*, 521, 5776

Fabrycky, D. & Tremaine, S. 2007, *ApJ*, 669, 1298

- Fabrycky, D. C., Lissauer, J. J., Ragozzine, D., et al. 2014, *ApJ*, 790, 146
- Fang, J. & Margot, J.-L. 2012, *ApJ*, 761, 92
- Faria, J. P., Haywood, R. D., Brewer, B. J., et al. 2016, *A&A*, 588, A31
- Feinstein, A. D., David, T. J., Montet, B. T., et al. 2022, *ApJL*, 925, L2
- Fellay, L., Pezzotti, C., Buldgen, G., Eggenberger, P., & Bolmont, E. 2023, *A&A*, 669, A2
- Feroz, F. & Hobson, M. P. 2008, *MNRAS*, 384, 449
- Feroz, F., Hobson, M. P., & Bridges, M. 2009, *MNRAS*, 398, 1601
- Feroz, F., Hobson, M. P., Cameron, E., & Pettitt, A. N. 2019, *The Open Journal of Astrophysics*, 2, 10
- Figueira, P., Faria, J. P., Silva, A. M., et al. 2025, *A&A*, 700, A174
- Figueira, P., Santos, N. C., Pepe, F., Lovis, C., & Nardetto, N. 2013, *A&A*, 557, A93
- Finociety, B., Donati, J.-F., Cristofari, P. I., et al. 2023, *MNRAS*, 526, 4627
- Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, *PASP*, 125, 306
- Fortier, A., Simon, A. E., Broeg, C., et al. 2024, *A&A*, 687, A302
- Fortney, J. J., Dawson, R. I., & Komacek, T. D. 2021, *Journal of Geophysical Research (Planets)*, 126, e06629
- Fortney, J. J., Marley, M. S., & Barnes, J. W. 2007, *ApJ*, 659, 1661
- Fossati, L., Haswell, C. A., Froning, C. S., et al. 2010, 714, L222
- Fox, C. & Wiegert, P. 2021, *MNRAS*, 501, 2378
- Gaia Collaboration. 2020, *VizieR Online Data Catalog*, I/350
- Gaia Collaboration, Vallenari, A., Brown, A. G. A., et al. 2022, *arXiv e-prints*, arXiv:2208.00211
- Gelman, A. & Rubin, D. B. 1992, *Statistical Science*, 7, 457
- Geweke, J. F. 1991, Evaluating the accuracy of sampling-based approaches to the calculation of posterior moments, Staff Report 148, Federal Reserve Bank of Minneapolis
- Gillon, M., Demory, B.-O., Van Grootel, V., et al. 2017, *Nature Astronomy*, 1, 0056
- Gillon, M., Pont, F., Moutou, C., et al. 2006, *A&A*, 459, 249
- Giménez, A. & Bastero, M. 1995, *Astrophys. Space Sci.*, 226, 99
- Ginzburg, S. & Sari, R. 2017, *MNRAS*, 469, 278

- Ginzburg, S., Schlichting, H. E., & Sari, R. 2018, *MNRAS*, 476, 759
- Goldberg, M. & Batygin, K. 2023, *ApJ*, 948, 12
- Goldberg, M., Batygin, K., & Morbidelli, A. 2022, *Icarus*, 388, 115206
- Goldreich, P. & Schlichting, H. E. 2014, *AJ*, 147, 32
- Goldreich, P. & Soter, S. 1966, *Icarus*, 5, 375
- Goodman, J. & Weare, J. 2010, *Communications in Applied Mathematics and Computational Science*, 5, 65
- Granata, V., Nascimbeni, V., Piotto, G., et al. 2014, *Astronomische Nachrichten*, 335, 797
- Guilluy, G., Giacobbe, P., Carleo, I., et al. 2022, *A&A*, 665, A104
- Gupta, A. & Schlichting, H. E. 2019, *MNRAS*, 487, 24
- Hadden, S. & Lithwick, Y. 2017, *AJ*, 154, 5
- Hagey, S. R., Edwards, B., & Boley, A. C. 2022, *AJ*, 164, 220
- Haldemann, J., Dorn, C., Venturini, J., Alibert, Y., & Benz, W. 2024, *A&A*, 681, A96
- Hamer, J. H. & Schlaufman, K. C. 2019, *AJ*, 158, 190
- Hamer, J. H. & Schlaufman, K. C. 2024, *The Astronomical Journal*, 167, 55
- Hammond, I., Christiaens, V., Price, D. J., et al. 2025, *MNRAS*, 539, 1613
- Hansen, B. M. S., Yu, T.-Y., & Hasegawa, Y. 2024, *The Open Journal of Astrophysics*, 7, 61
- Harre, J. V., Smith, A. M. S., Barros, S. C. C., et al. 2023, *A&A*, 669, A124
- Hartmann, L. W. & Noyes, R. W. 1987, *ARA&A*, 25, 271
- Haswell, C. A., Fossati, L., Ayres, T., et al. 2012, *The Astrophysical Journal*, 760, 79
- Hatzes, A. P. 2016, in *Astrophysics and Space Science Library*, Vol. 428, *Methods of Detecting Exoplanets: 1st Advanced School on Exoplanetary Science*, ed. V. Bozza, L. Mancini, & A. Sozzetti, 3
- Haywood, R. D., Collier Cameron, A., Queloz, D., et al. 2014, *MNRAS*, 443, 2517
- Hebb, L., Collier-Cameron, A., Loeillet, B., et al. 2009, *ApJ*, 693, 1920
- Henry, G. W., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2000, 529, L41
- Hilditch, R. W. 2001, *An Introduction to Close Binary Stars*
- Himes, M. D. & Harrington, J. 2022, *ApJ*, 931, 86
- Hobson, M. J., Suárez Mascareño, A., Lovis, C., et al. 2025, *A&A*, 702, A32

- Høg, E., Fabricius, C., Makarov, V. V., et al. 2000, *A&A*, 355, L27
- Holman, M. J., Fabrycky, D. C., Ragozzine, D., et al. 2010, *Science*, 330, 51
- Holman, M. J. & Murray, N. W. 2005, *Science*, 307, 1288
- Howard, A. W., Marcy, G. W., Bryson, S. T., et al. 2012, 201, 15
- Howe, A. R., Becker, J. C., Stark, C. C., & Adams, F. C. 2025, arXiv e-prints, arXiv:2501.08191
- Howell, S. B., Sobeck, C., Haas, M., et al. 2014, *PASP*, 126, 398
- Hoyer, S., Guterman, P., Demangeon, O., et al. 2020, *A&A*, 635, A24
- Hoyer, S., Pallé, E., Dragomir, D., & Murgas, F. 2016, *The Astronomical Journal*, 151, 137
- Huang, S. & Ormel, C. W. 2023, *MNRAS*, 522, 828
- Husnoo, N., Pont, F., Mazeh, T., et al. 2012, *MNRAS*, 422, 3151
- Husser, T. O., Wende-von Berg, S., Dreizler, S., et al. 2013, *A&A*, 553, A6
- Hut, P. 1981, *A&A*, 99, 126
- Ida, S. & Lin, D. N. C. 2004, *ApJ*, 604, 388
- Ivshina, E. S. & Winn, J. N. 2022, *ApJS*, 259, 62
- Izidoro, A., Bitsch, B., Raymond, S. N., et al. 2021, *A&A*, 650, A152
- Izidoro, A., Ogihara, M., Raymond, S. N., et al. 2017, *MNRAS*, 470, 1750
- Jackson, B., Greenberg, R., & Barnes, R. 2008, *ApJ*, 678, 1396
- Jackson, B., Jensen, E., Peacock, S., Arras, P., & Penev, K. 2016, *Celestial Mechanics and Dynamical Astronomy*, 126, 227
- Jeffries, R. D., Jackson, R. J., Wright, N. J., et al. 2023, *MNRAS*, 523, 802
- Jenkins, J. M., Twicken, J. D., McCauliff, S., et al. 2016, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 9913, *Software and Cyber-infrastructure for Astronomy IV*, ed. G. Chiozzi & J. C. Guzman, 99133E
- Johnstone, C. P., Bartel, M., & Güdel, M. 2021, *A&A*, 649, A96
- Karalis, A., Lee, E. J., & Thorngren, D. P. 2024, *The Astrophysical Journal*, 978, 46
- Kass, R. E. & Raftery, A. E. 1995, *Journal of the American Statistical Association*, 90, 773
- Kempton, E. M. R., Bean, J. L., Louie, D. R., et al. 2018, *PASP*, 130, 114401

- Kipping, D. M. 2009a, MNRAS, 392, 181
- Kipping, D. M. 2009b, MNRAS, 396, 1797
- Kipping, D. M. 2013, Monthly Notices of the Royal Astronomical Society, 435, 2152
- Kley, W. & Nelson, R. P. 2012, ARA&A, 50, 211
- Kopparapu, R. K., Hébrard, E., Belikov, R., et al. 2018, The Astrophysical Journal, 856, 122
- Kraus, A. L., Cody, A. M., Covey, K. R., et al. 2015, ApJ, 807, 3
- Kreidberg, L., Line, M. R., Bean, J. L., et al. 2015, ApJ, 814, 66
- Krenn, A. F., Kubyshkina, D., Fossati, L., et al. 2024, A&A, 686, A301
- Kubyshkina, D., Fossati, L., Erkaev, N. V., et al. 2018, A&A, 619, A151
- Kubyshkina, D. & Vidotto, A. A. 2021, MNRAS, 504, 2034
- Kubyshkina, D. I. & Fossati, L. 2021, Research Notes of the American Astronomical Society, 5, 74
- Kulow, J. R., France, K., Linsky, J., & Parke Loyd, R. O. 2014, The Astrophysical Journal, 786, 132
- Kurucz, R. L. 1993, SYNTHE spectrum synthesis programs and line data (Smithsonian Astrophysical Observatory)
- Lacedelli, G., Malavolta, L., Borsato, L., et al. 2021, MNRAS, 501, 4148
- Lai, D., Helling, C., & van den Heuvel, E. P. J. 2010, ApJ, 721, 923
- Lambrechts, M., Morbidelli, A., Jacobson, S. A., et al. 2019, A&A, 627, A83
- Lanza, A. F. 2020, Monthly Notices of the Royal Astronomical Society, 497, 3911
- Lanza, A. F., Damiani, C., & Gandolfi, D. 2011, A&A, 529, A50
- Laskar, J. 1997, A&A, 317, L75
- Laskar, J. 2000, Phys. Rev. Lett., 84, 3240
- Laskar, J. & Petit, A. C. 2017, A&A, 605, A72
- Latham, D. W., Rowe, J. F., Quinn, S. N., et al. 2011, ApJL, 732, L24
- Lee, E. J., Chiang, E., & Ormel, C. W. 2014, ApJ, 797, 95
- Lee, M. H. & Peale, S. J. 2002, Extrasolar Planets and Mean-Motion Resonances
- Leleu, A., Alibert, Y., Hara, N. C., et al. 2021, A&A, 649, A26
- Leleu, A., Delisle, J. B., Delrez, L., et al. 2024, A&A, 688, A211

Leonardi, P., Borsato, L., Pagliaro, L., et al. 2025, arXiv e-prints, arXiv:2509.14156

Leonardi, P., Nascimbeni, V., Granata, V., et al. 2024, *A&A*, 686, A84

Levrard, B., Winisdoerffer, C., & Chabrier, G. 2009, *ApJL*, 692, L9

Li, S.-L., Miller, N., Lin, D. N. C., & Fortney, J. J. 2010, *Nature*, 463, 1054

Lin, D. N. C., Bodenheimer, P., & Richardson, D. C. 1996, *Nature*, 380, 606

Lind, K., Asplund, M., & Barklem, P. S. 2009, *A&A*, 503, 541

Lindegren, L., Bastian, U., Biermann, M., et al. 2021, *A&A*, 649, A4

Lithwick, Y., Xie, J., & Wu, Y. 2012, *The Astrophysical Journal*, 761, 122

Liu, B., Raymond, S. N., & Jacobson, S. A. 2022, *Nature*, 604, 643

Lopez, E. D. & Fortney, J. J. 2014, *ApJ*, 792, 1

Lopez, E. D., Fortney, J. J., & Miller, N. 2012, *ApJ*, 761, 59

Lovis, C. & Mayor, M. 2007, *A&A*, 472, 657

Luger, R., Agol, E., Kruse, E., et al. 2016, *AJ*, 152, 100

Luger, R., Kruse, E., Foreman-Mackey, D., Agol, E., & Saunders, N. 2018, *AJ*, 156, 99

Lund, M. N., Knudstrup, E., Aguirre, V. S., et al. 2019, *The Astronomical Journal*, 158, 248

Luque, R., Osborn, H. P., Leleu, A., et al. 2023, *Nature*, 623, 932

Luque, R. & Pallé, E. 2022, *Science*, 377, 1211

Léger, A., Selsis, F., Sotin, C., et al. 2004, *Icarus*, 169, 499

MacDonald, M. G. & Dawson, R. I. 2018, *AJ*, 156, 228

Maciejewski, G., Dimitrov, D., Fernández, M., et al. 2016, *A&A*, 588, L6

Maciejewski, G., Errmann, R., Raetz, S., et al. 2011, *A&A*, 528, A65

Maciejewski, G., Fernández, M., Aceituno, F., et al. 2018, *Acta Astron.*, 68, 371

Madhusudhan, N. 2019, *ARA&A*, 57, 617

Maggio, A., Locci, D., Pillitteri, I., et al. 2022, *The Astrophysical Journal*, 925, 172

Maggio, A., Pillitteri, I., Argiroffi, C., et al. 2023, *The Astrophysical Journal*, 951, 18

Malavolta, L., Mayo, A. W., Loudén, T., et al. 2018, *AJ*, 155, 107

Malavolta, L., Nascimbeni, V., Piotto, G., et al. 2016, *A&A*, 588, A118

- Malhotra, R. 1993a, *Nature*, 365, 819
- Malhotra, R. 1993b, *Nature*, 365, 819
- Mallon, M., von Essen, C., Herrero, E., et al. 2019, *A&A*, 622, A81
- Mallorquín, M., Béjar, V. J. S., Lodieu, N., et al. 2023, *A&A*, 671, A163
- Mantovan, G., Malavolta, L., Desidera, S., et al. 2024a, *A&A*, 682, A129
- Mantovan, G., Malavolta, L., Locci, D., et al. 2024b, *A&A*, 684, L17
- Marconi, A., Abreu, M., Adibekyan, V., et al. 2024, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 13096, *Ground-based and Airborne Instrumentation for Astronomy X*, ed. J. J. Bryant, K. Motohara, & J. R. D. Vernet, 1309613
- Marigo, P., Girardi, L., Bressan, A., et al. 2017, *ApJ*, 835, 77
- Marinelli, M. & Green, J. 2024, in *WFC3 Instrument Handbook for Cycle 33 v. 17*, Vol. 17, 17
- Matsumura, S., Peale, S. J., & Rasio, F. A. 2010, *The Astrophysical Journal*, 725, 1995
- Mayor, M., Pepe, F., Queloz, D., et al. 2003, *The Messenger*, 114, 20
- Mayor, M. & Queloz, D. 1995, 378, 355
- Meibom, S., Barnes, S. A., Platais, I., et al. 2015, *Nature*, 517, 589
- Meibom, S. & Mathieu, R. D. 2005, *ApJ*, 620, 970
- Melita, M. D. & Woolfson, M. M. 1996, *MNRAS*, 280, 854
- Millholland, S. & Laughlin, G. 2018, *ApJL*, 869, L15
- Miralda-Escudé, J. 2002, *ApJ*, 564, 1019
- Miyazaki, S. & Masuda, K. 2023, *AJ*, 166, 209
- Mordasini, C. 2020, *A&A*, 638, A52
- Mortier, A., Bonomo, A. S., Rajpaul, V. M., et al. 2018, *MNRAS*, 481, 1839
- Morton, T. D. 2015, *isochrones: Stellar model grid package*, *Astrophysics Source Code Library*, record ascl:1503.010
- Moutou, C., Ould-Elhkim, M., Donati, J.-F., et al. 2024, *A&A*, 688, A196
- Nagasawa, M., Ida, S., & Bessho, T. 2008, *ApJ*, 678, 498
- Nardiello, D., Akana Murphy, J. M., Spinelli, R., et al. 2025, *A&A*, 693, A32
- Nardiello, D., Deleuil, M., Mantovan, G., et al. 2021, *MNRAS*, 505, 3767



- Nardiello, D., Malavolta, L., Desidera, S., et al. 2022, *A&A*, 664, A163
- Nascimbeni, V., Borsato, L., Leonardi, P., et al. 2024, *A&A*, 690, A349
- Nascimbeni, V., Borsato, L., Zingales, T., et al. 2023, *A&A*, 673, A42
- Nascimbeni, V., Cunial, A., Murabito, S., et al. 2013, *A&A*, 549, A30
- Nascimbeni, V., Piotto, G., Bedin, L. R., & Damasso, M. 2011, *A&A*, 527, A85
- Nascimbeni, V., Piotto, G., Börner, A., et al. 2022, *A&A*, 658, A31
- Nelson, B., Ford, E. B., & Payne, M. J. 2014, *ApJS*, 210, 11
- Nelson, R. P., Papaloizou, J. C. B., Masset, F., & Kley, W. 2000, *MNRAS*, 318, 18
- Netto, Y., Lorenzo-Oliveira, D., Meléndez, J., et al. 2021, *The Astronomical Journal*, 162, 160
- Newton, E. R., Mann, A. W., Tofflemire, B. M., et al. 2019, *ApJL*, 880, L17
- Nichols, J. D., Wynn, G. A., Goad, M., et al. 2015, *ApJ*, 803, 9
- Ogilvie, G. I. & Lin, D. N. C. 2007, *ApJ*, 661, 1180
- Oklopčić, A. & Hirata, C. M. 2018, *ApJL*, 855, L11
- Orell-Miquel, J., Nowak, G., Murgas, F., et al. 2023, *A&A*, 669, A40
- Otegi, J. F., Helled, R., & Bouchy, F. 2022, *A&A*, 658, A107
- Owen, J. E. 2020, *MNRAS*, 498, 5030
- Owen, J. E. & Wu, Y. 2013, *ApJ*, 775, 105
- Owen, J. E. & Wu, Y. 2017, *ApJ*, 847, 29
- Parmentier, V., Line, M. R., Bean, J. L., et al. 2018, *A&A*, 617, A110
- Parviainen, H. & Aigrain, S. 2015, *MNRAS*, 453, 3821
- Parviainen, H., Luque, R., & Pallé, E. 2023, *Monthly Notices of the Royal Astronomical Society*, 527, 5693
- Parviainen, H., Pallé, E., Nortmann, L., et al. 2016, *A&A*, 585, A114
- Patra, K. C., Winn, J. N., Holman, M. J., et al. 2020, 159, 150
- Patra, K. C., Winn, J. N., Holman, M. J., et al. 2017, 154, 4
- Paulson, D. B., Cochran, W. D., & Hatzes, A. P. 2004, *The Astronomical Journal*, 127, 3579
- Paxton, B., Bildsten, L., Dotter, A., et al. 2011, *ApJS*, 192, 3

- Paxton, B., Cantiello, M., Arras, P., et al. 2013, *ApJS*, 208, 4
- Paxton, B., Schwab, J., Bauer, E. B., et al. 2018, *ApJS*, 234, 34
- Paxton, B., Smolec, R., Schwab, J., et al. 2019, *ApJS*, 243, 10
- Penev, K., Bouma, L. G., Winn, J. N., & Hartman, J. D. 2018, *AJ*, 155, 165
- Pepe, F., Mayor, M., Rupprecht, G., et al. 2002, *The Messenger*, 110, 9
- Pepe, F., Molaro, P., Cristiani, S., et al. 2014, *Astronomische Nachrichten*, 335, 8
- Perryman, M. 2018, *The Exoplanet Handbook*
- Petit, A. C., Laskar, J., & Boué, G. 2018, *A&A*, 617, A93
- Petrovich, C., Deibert, E., & Wu, Y. 2019, *AJ*, 157, 180
- Piro, A. L. & Vissapragada, S. 2020, *The Astronomical Journal*, 159, 131
- Plavchan, P., Barclay, T., Gagné, J., et al. 2020, *Nature*, 582, 497
- Poddaný, S., Brát, L., & Pejcha, O. 2010, *New Astron.*, 15, 297
- Poppenhaeger, K., Ketzer, L., & Mallonn, M. 2021, *MNRAS*, 500, 4560
- Pu, B. & Wu, Y. 2015, *ApJ*, 807, 44
- Queloz, D. 1995, in *IAU Symposium*, Vol. 167, *New Developments in Array Technology and Applications*, ed. A. G. D. Philip, K. Janes, & A. R. Upgren, 221
- Quinn, S. N., White, R. J., Latham, D. W., et al. 2012, *ApJL*, 756, L33
- Quinn, S. N., White, R. J., Latham, D. W., et al. 2014, *The Astrophysical Journal*, 787, 27
- Ragozzine, D. & Holman, M. J. 2010, in *AAS/Division of Dynamical Astronomy Meeting*, Vol. 41, *AAS/Division of Dynamical Astronomy Meeting #41*, 4.07
- Ragozzine, D. & Wolf, A. S. 2009, *ApJ*, 698, 1778
- Rajpaul, V., Aigrain, S., Osborne, M. A., Reece, S., & Roberts, S. 2015, *MNRAS*, 452, 2269
- Rasio, F. A., Tout, C. A., Lubow, S. H., & Livio, M. 1996, *ApJ*, 470, 1187
- Rein, H. & Liu, S. F. 2012, *A&A*, 537, A128
- Rein, H. & Tamayo, D. 2016, *MNRAS*, 459, 2275
- Reza, A., Kubyshkina, D., Fossati, L., & Helling, C. 2025, *A&A*, 694, A88
- Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, *Journal of Astronomical Telescopes, Instruments, and Systems*, 1, 014003
- Rogers, J. G. 2025, *MNRAS*, 539, 2230

- Rogers, J. G., Schlichting, H. E., & Owen, J. E. 2023, *ApJL*, 947, L19
- Rosário, N. M., Barros, S. C. C., Demangeon, O. D. S., & Santos, N. C. 2022, *A&A*, 668, A114
- Roy, A., Chakraborty, A., Mahadevan, S., et al. 2016, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 9908, *Ground-based and Airborne Instrumentation for Astronomy VI*, ed. C. J. Evans, L. Simard, & H. Takami, 99086R
- Saar, S. H. & Donahue, R. A. 1997, *ApJ*, 485, 319
- Salmon, S. J. A. J., Van Grootel, V., Buldgen, G., Dupret, M. A., & Eggenberger, P. 2021, *A&A*, 646, A7
- Santerne, A., Malavolta, L., Kosiarek, M. R., et al. 2019, *arXiv e-prints*, arXiv:1911.07355
- Santos, N. C., Sousa, S. G., Mortier, A., et al. 2013, *A&A*, 556, A150
- Sartoretti, P. & Schneider, J. 1999, *A&AS*, 134, 553
- Sasselov, D. D. 2003, *ApJ*, 596, 1327
- Sato, B., Izumiura, H., Toyota, E., et al. 2007, *The Astrophysical Journal*, 661, 527
- Saunders, N., Grunblatt, S. K., Huber, D., et al. 2022, *AJ*, 163, 53
- Schanche, N., Hébrard, G., Collier Cameron, A., et al. 2020, *MNRAS*, 499, 428
- Schwarz, G. 1978, *The Annals of Statistics*, 6, 461
- Schwarz, G. 1978, *Annals of Statistics*, 6, 461
- Scuflaire, R., Théado, S., Montalbán, J., et al. 2008, *Astrophys. Space Sci.*, 316, 83
- Seager, S. & Mallén-Ornelas, G. 2003, *ApJ*, 585, 1038
- Sestito, P. & Randich, S. 2005, *A&A*, 442, 615
- Shen, N. & González, B. 2021, *arXiv e-prints*, arXiv:2104.14725
- Siegel, J. C. & Fabrycky, D. 2021, *AJ*, 161, 290
- Sikora, J., Rowe, J., Barat, S., et al. 2023, *The Astronomical Journal*, 165, 250
- Silburt, A., Gaidos, E., & Wu, Y. 2015, *ApJ*, 799, 180
- Simola, U., Bonfanti, A., Dumusque, X., et al. 2022, *A&A*, 664, A127
- Simola, U., Dumusque, X., & Cisewski-Kehe, J. 2019, *A&A*, 622, A131
- Skilling, J. 2006, *Bayesian Analysis*, 1, 833
- Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, *The Astronomical Journal*, 131, 1163

- Snedden, C. A. 1973, PhD thesis, University of Texas, Austin
- Sousa, S. G. 2014, in *Determination of Atmospheric Parameters of B* (Springer), 297–310
- Sousa, S. G., Adibekyan, V., Delgado-Mena, E., et al. 2021, *A&A*, 656, A53
- Sousa, S. G., Santos, N. C., Adibekyan, V., Delgado-Mena, E., & Israelian, G. 2015, *A&A*, 577, A67
- Sousa, S. G., Santos, N. C., Israelian, G., Mayor, M., & Monteiro, M. J. P. F. G. 2007, *A&A*, 469, 783
- Sousa, S. G., Santos, N. C., Mayor, M., et al. 2008, *A&A*, 487, 373
- Southworth, J., Barker, A. J., Hinse, T. C., et al. 2022, *MNRAS*, 515, 3212
- Southworth, J., Wheatley, P. J., & Sams, G. 2007, *MNRAS*, 379, L11
- Spada, F., Demarque, P., Kim, Y. C., & Sills, A. 2013, *ApJ*, 776, 87
- Stangret, M., Casasayas-Barris, N., Pallé, E., et al. 2022, *A&A*, 662, A101
- Steffen, J. H., Ford, E. B., Rowe, J. F., et al. 2012, *The Astrophysical Journal*, 756, 186
- Stock, J. W., Kitzmann, D., Patzer, A. B. C., & Sedlmayr, E. 2018, *Monthly Notices of the Royal Astronomical Society*
- Storn, R. & Price, K. V. 1997, *J. Glob. Optim.*, 11, 341
- Suárez Mascareño, A., Damasso, M., Lodieu, N., et al. 2021, *Nature Astronomy*, 6, 232
- Sulis, S., Borsato, L., Grouffal, S., et al. 2024, *A&A*, 686, L18
- Tamayo, D., Rein, H., Petrovich, C., & Murray, N. 2017, *The Astrophysical Journal Letters*, 840, L19
- ter Braak, C. J. F. & Vrugt, J. A. 2008, *Statistics and Computing*, 18, 435
- Thiabaud, A., Marboeuf, U., Alibert, Y., Leya, I., & Mezger, K. 2015, *A&A*, 574, A138
- Tran, Q. H., Bowler, B. P., Cochran, W. D., et al. 2021, *The Astronomical Journal*, 161, 173
- Trotta, R. 2007, *Monthly Notices of the Royal Astronomical Society*, 378, 72–82
- Tsiaras, A., Rocchetto, M., Waldmann, I. P., et al. 2016a, *ApJ*, 820, 99
- Tsiaras, A., Waldmann, I. P., Rocchetto, M., et al. 2016b, *ApJ*, 832, 202
- Tsiaras, A., Waldmann, I. P., Zingales, T., et al. 2018, *AJ*, 155, 156
- Turner, J. D., Flagg, L., Ridden-Harper, A., & Jayawardhana, R. 2022, *AJ*, 163, 281
- Turner, J. D., Ridden-Harper, A., & Jayawardhana, R. 2021, *AJ*, 161, 72

- Unger, N., Ségransan, D., Queloz, D., et al. 2021, *A&A*, 654, A104
- Vach, S., Zhou, G., Huang, C. X., et al. 2024, *The Astronomical Journal*, 167, 210
- Valsecchi, F., Rappaport, S., Rasio, F. A., Marchant, P., & Rogers, L. A. 2015, *The Astrophysical Journal*, 813, 101
- Valsecchi, F., Rasio, F. A., & Steffen, J. H. 2014, *The Astrophysical Journal Letters*, 793, L3
- Van Eylen, V., Albrecht, S., Huang, X., et al. 2019, *AJ*, 157, 61
- Vanderburg, A., Becker, J. C., Kristiansen, M. H., et al. 2016, *ApJL*, 827, L10
- Vissapragada, S., Chontos, A., Greklek-McKeon, M., et al. 2022, *The Astrophysical Journal Letters*, 941, L31
- Vissapragada, S., Stefánsson, G., Greklek-McKeon, M., et al. 2021, *The Astronomical Journal*, 162, 222
- Wahl, S. M., Thorngren, D., Lu, T., & Militzer, B. 2021, *ApJ*, 921, 105
- Weinberg, N. N., Davachi, N., Essick, R., et al. 2023, *arXiv e-prints*, arXiv:2305.11974
- Weinberg, N. N., Sun, M., Arras, P., & Essick, R. 2017, *ApJL*, 849, L11
- Weiss, L. M., Isaacson, H. T., Marcy, G. W., et al. 2018, *The Astronomical Journal*, 156, 254
- Weiss, L. M., Millholland, S. C., Petigura, E. A., et al. 2023, in *Astronomical Society of the Pacific Conference Series*, Vol. 534, *Protostars and Planets VII*, ed. S. Inutsuka, Y. Aikawa, T. Muto, K. Tomida, & M. Tamura, 863
- Werner, M. W., Roellig, T. L., Low, F. J., et al. 2004, *ApJS*, 154, 1
- Winn, J. N. 2010, *arXiv e-prints*, arXiv:1001.2010
- Winn, J. N., Holman, M. J., Bakos, G. Á., et al. 2007a, *AJ*, 134, 1707
- Winn, J. N., Holman, M. J., Henry, G. W., et al. 2007b, *AJ*, 133, 1828
- Winn, J. N. & Stefánsson, G. 2025, *arXiv e-prints*, arXiv:2510.05229
- Wong, I., Shporer, A., Vissapragada, S., et al. 2022, *AJ*, 163, 175
- Wong, I., Shporer, A., Zhou, G., et al. 2021, *The Astronomical Journal*, 162, 256
- Wong, K. H. & Lee, M. H. 2024, *The Astronomical Journal*, 167, 112
- Wood, M. L., Mann, A. W., Barber, M. G., et al. 2023, *The Astronomical Journal*, 165, 85
- Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, *AJ*, 140, 1868
- Wu, Y. & Lithwick, Y. 2011, *ApJ*, 735, 109

- Wu, Y., Malhotra, R., & Lithwick, Y. 2024, *The Astrophysical Journal*, 971, 5
- Xu, W. & Lai, D. 2017, *MNRAS*, 468, 3223
- Yang, F. & Chary, R.-R. 2022, *AJ*, 164, 259
- Yee, S. W., Winn, J. N., & Hartman, J. D. 2021, *AJ*, 162, 240
- Yee, S. W., Winn, J. N., Hartman, J. D., et al. 2022, *AJ*, 164, 70
- Yee, S. W., Winn, J. N., Knutson, H. A., et al. 2019, 888, L5
- Zahn, J. P. 1977, *A&A*, 57, 383
- Zahn, J. P. 2008, in *EAS Publications Series*, Vol. 29, *EAS Publications Series*, ed. M. J. Goupil & J. P. Zahn, 67–90
- Zeng, L., Jacobsen, S. B., Sasselov, D. D., et al. 2019, *Proceedings of the National Academy of Science*, 116, 9723
- Zhou, G., Wirth, C. P., Huang, C. X., et al. 2022, *The Astronomical Journal*, 163, 289