



UNIVERSIDAD DE CONCEPCIÓN
FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS

OBSERVATIONAL CHARACTERIZATION AND VALIDATION OF HOT JUPITERS: FROM ATMOSPHERIC SIGNATURES IN TOI-1019 TO THE CONFIRMATION OF TESS CANDIDATES IN PLATO FIELD

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Resumen

La caracterización física de exoplanetas gigantes irradiados constituye una herramienta fundamental para comprender los procesos de formación, evolución y estructura de los sistemas planetarios. Esta tesis tuvo como objetivo caracterizar tres planetas gigantes de período corto mediante la combinación de espectroscopía de transmisión, fotometría de tránsito y mediciones de velocidad radial de alta precisión.

El primer estudio presenta la primera caracterización atmosférica del planeta TOI-1019 b utilizando espectroscopía de transmisión óptica obtenida con IMACS. Los resultados son compatibles con procesos de dispersión atmosférica y no muestran evidencia significativa de absorción por Na o K dentro de la precisión alcanzada, lo que motiva futuras observaciones con mayor cobertura espectral y sensibilidad.

El segundo estudio corresponde a una caracterización física refinada de TOI-6105 b y Gaia-7 b mediante el análisis conjunto de fotometría de tránsito obtenida por TESS y observatorios terrestres, junto con observaciones de velocidad radial de HARPS y CORALIE. Este análisis permitió mejorar la determinación de sus parámetros físicos y orbitales, contribuyendo a la caracterización de planetas gigantes pertenecientes al campo LOPS2 de la misión PLATO.

En conjunto, los resultados demuestran que la combinación de técnicas observacionales complementarias permite obtener una caracterización más completa de exoplanetas gigantes irradiados y aporta nuevas restricciones observacionales para el estudio de sus atmósferas, estructura interna y evolución.

Keywords – Exoplanetas; Júpiteres calientes; Espectroscopía de transmisión; Velocidad radial; Fotometría de tránsito; Atmósferas planetarias; PLATO LOPS2.

Abstract

The physical characterization of irradiated giant exoplanets provides fundamental constraints on planetary formation, evolution, and internal structure. This thesis aimed to characterize three short-period giant planets through the combined use of transmission spectroscopy, transit photometry, and high-precision radial velocity measurements.

The first study presents the first atmospheric characterization of TOI-1019 b using ground-based optical transmission spectroscopy obtained with IMACS. The measured transmission spectrum is consistent with atmospheric scattering and shows no statistically significant Na or K absorption within the precision of the observations, motivating future observations with broader wavelength coverage and higher sensitivity.

The second study presents a refined physical characterization of TOI-6105 b and Gaia-7 b through a joint analysis of TESS and ground-based transit photometry together with HARPS and CORALIE radial velocity observations. The resulting analysis improves the determination of their physical and orbital parameters and contributes to the characterization of giant planets located in the PLATO Long Observation Field South (LOPS2).

Overall, these studies demonstrate that combining complementary observational techniques provides a more comprehensive characterization of irradiated giant exoplanets and contributes new observational constraints on their atmospheres, internal structure, and evolution.

Keywords – Exoplanets; Hot Jupiters; Transmission spectroscopy; Radial velocity; Transit photometry; Planetary atmospheres; PLATO LOPS2.

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Chapter 1

Introduction

1.1 Exoplanets: From Discovery to Physical Characterization

Since the discovery of 51 Pegasi b (Mayor and Queloz, 1995), exoplanetary science has evolved into one of the fastest-growing fields of modern astrophysics (e.g., Fischer et al., 2016; Madhusudhan, 2019). Thousands of exoplanets (over 6000 according to *NASA Exoplanet Archive*¹) spanning a broad range of masses, radii, orbital architectures, and equilibrium temperatures have now been discovered, revealing that planetary systems are far more diverse than previously anticipated from the Solar System alone. Consequently, the field has progressively shifted from the mere detection of exoplanets toward their detailed physical characterization, with the aim of understanding how planets form, evolve, and interact with their host stars.

This diversity encompasses compact multi-planet systems, giant planets orbiting within only a few days of their host stars, planets spanning more than an order of magnitude in bulk density, and atmospheres exhibiting a wide variety of chemical compositions. These discoveries have challenged classical theories of planet formation and evolution, motivating increasingly sophisticated observational and theoretical efforts to explain the origin of planetary diversity.

Among the known exoplanet population, irradiated giant planets—and particularly

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

hot Jupiters—constitute exceptional laboratories for studying planetary physics under extreme irradiation. Their large radii, extended atmospheres, and frequent transits produce strong observational signals that make them particularly well suited for detailed photometric, spectroscopic, and atmospheric studies (see [Fortney et al., 2021](#), and references therein). As a result, hot Jupiters have become fundamental targets for investigating planetary structure, atmospheric chemistry, migration mechanisms, and evolutionary processes.

Addressing these questions requires complementary observational techniques capable of constraining different physical properties of planetary systems, because no single observational technique can constrain every relevant planetary property. Instead, transit photometry provides precise measurements of planetary radii and orbital geometry, radial velocity observations constrain planetary masses and bulk densities, while transmission spectroscopy probes atmospheric composition and scattering processes. Together, these techniques enable a comprehensive physical characterization of irradiated giant planets and provide key observational constraints on models of planetary formation and evolution.

This thesis is built around two independent observational studies aimed at the physical characterization of irradiated giant planets. The first presents the atmospheric characterization of TOI-1019 b using transmission spectroscopy, while the second focuses on refining the physical and orbital parameters of TOI-6105 b and *Gaia*-7b through transit photometry and radial velocity observations. Although the two studies address different systems and observational problems, they are connected by a common scientific goal: understanding how the physical properties and irradiation of giant planets determine both their observable atmospheric signatures and their suitability for detailed atmospheric characterization. In this context, the first study probes the atmospheric response of an irradiated giant planet directly, while the second establishes the physical and orbital properties that govern the detectability and interpretation of atmospheric signals in comparable systems.

1.2 Open Questions in Irradiated Giant Planet Physics

Despite the remarkable progress achieved over the past three decades, several fundamental questions concerning irradiated giant planets remain unresolved. Hot Jupiters (HJs) and ultra-hot Jupiters (UHJs) provide unique laboratories for studying planetary physics under extreme irradiation, yet many aspects of their origin, structure, atmospheres, and long-term evolution remain poorly understood.

Among the most important open problems are the physical mechanism responsible for the radius inflation observed in many HJs, the dominant formation and migration pathways that place giant planets on short-period orbits, the origin of the diversity observed in their atmospheric compositions and thermal structures, and the relationship between planetary properties and those of their host stars. These questions are closely connected, as atmospheric chemistry, planetary interiors, and orbital evolution all provide complementary information on the evolutionary history of giant planets.

1.2.1 Probing exoplanet atmospheres through transit observations

Transmission spectroscopy has become one of the primary techniques for probing the atmospheres of transiting exoplanets (e.g., [Seager and Deming, 2010](#); [Madhusudhan, 2019](#); [Rustamkulov et al., 2023](#)). During a planetary transit, a small fraction of the stellar light passes through the planet’s atmosphere before reaching the observer. Because atmospheric opacity depends on wavelength, the apparent planetary radius varies across the spectrum, producing the so-called transmission spectrum. This wavelength dependence enables the detection of atomic and molecular absorbers, scattering processes, and clouds or hazes, thereby providing direct constraints on atmospheric composition and structure.

The transit depth is defined as $\delta = \Delta F/F$ and, to first order, is related to the planet-to-star radius ratio through $\delta \simeq (R_p/R_\star)^2$. Since the atmosphere is partially transparent, the effective planetary radius becomes wavelength dependent, $R_p(\lambda)$, causing small variations in the observed transit depth that encode information about the atmospheric properties.

To first order, the expected amplitude of an atmospheric absorption feature is proportional to the atmospheric scale height H , and can be approximated as

$$\Delta\delta/\delta \simeq 2(H/R_p), \quad (1.2.1)$$

where $H = k_B T / (\mu g)$ is the atmospheric scale height, with T the atmospheric temperature, μ the mean molecular weight, and g the planetary surface gravity.

Despite its remarkable success, detailed atmospheric characterization has been achieved for only a small fraction of the known hot Jupiter population. Expanding this sample is essential for establishing robust population-level trends and testing theoretical models of atmospheric evolution, planetary formation, and radius inflation.

Within this context, this thesis investigates three irradiated giant planets from complementary observational perspectives. Multi-wavelength transmission spectroscopy with IMACS is used to investigate the atmosphere of TOI-1019 b, while transit photometry and high-resolution radial velocity observations with HARPS provide accurate physical and orbital parameters for TOI-6105 b and *Gaia*-7b. Together, these studies examine different stages of the characterization process, from establishing the atmospheric observability of an irradiated giant planet to determining the physical properties that control the amplitude and interpretation of atmospheric signals. This provides a common framework for assessing how planetary radius, mass, surface gravity, and irradiation shape the prospects for atmospheric characterization of close-in giant planets.

1.3 Research Objectives

1.3.1 General Objectives

To investigate the physical and atmospheric properties of irradiated giant planets by combining observational constraints on their bulk properties, orbital architecture, and atmospheric signatures in the context of large-scale space-based photometric surveys.

1.3.2 Specific Objectives

Project I – Atmospheric Characterization

1. Analyze time-series spectrophotometric observations of a transiting hot Jupiter detected by TESS.
2. Measure wavelength-dependent transit depths and construct a transmission spectrum.
3. Constrain atmospheric features consistent with scattering processes or atomic absorption.
4. Evaluate the robustness of atmospheric inferences through Bayesian modeling and noise analysis.
5. Assess the implications of the derived atmospheric properties within the context of irradiated giant planet physics.

Project II – Radial Velocity Confirmation and Dynamical Characterization

6. Obtain and analyze high-resolution radial velocity measurements of hot Jupiter candidates located in southern survey fields.
7. Determine planetary masses and refine orbital parameters through joint photometric and spectroscopic modeling.
8. Evaluate radial velocity follow-up strategies in preparation for future space missions.
9. Contribute to the validation and physical characterization of giant planets around bright southern stars.

1.4 Research Hypotheses

This thesis is guided by the following scientific hypotheses, formulated as testable questions associated with the atmospheric and physical characterization of irradiated giant exoplanets.

Project I – Atmospheric Characterization of TOI-1019 b

The optical transmission spectrum of TOI-1019 b contains measurable wavelength-dependent features that can be attributed to atmospheric scattering and/or atomic absorption, providing observational constraints on the atmospheric properties of the planet.

Project II – Physical Characterization of TOI-6105 b and Gaia-7b

TOI-6105 b and *Gaia*-7b are expected to exhibit physical properties consistent with inflated, highly irradiated giant planets, which can be constrained through the combined analysis of transit photometry and high-precision radial velocity observations.

1.5 Thesis Structure

This thesis is organized as follows: Chapter 2 presents the theoretical framework for this work. Chapter 3 describes the methodology that was employed. Chapter 4 presents the results for the project related to TOI-1019. Chapter 5 presents the results associated to the project for TOI-6105 and Gaia 7 b/TOI-6409. Finally, Chapter 6 discusses the findings and conclusions obtained for this thesis.

Chapter 2

Theoretical Framework

2.1 Definition and physical nature of exoplanets

2.1.1 What is an exoplanet?

An exoplanet is a planetary body orbiting a star other than the Sun, and therefore located outside the Solar System. Since the first confirmed detection of an exoplanet orbiting a solar-type star in 1995 (51 Peg b; [Mayor and Queloz 1995](#)), the study of exoplanets has evolved from the discovery of individual systems to the physical characterization of planetary populations. The rapid increase in the number of confirmed planets, together with advances in photometric, spectroscopic, and radial velocity instrumentation, has shifted the focus of the field toward understanding the internal structure, atmospheric properties, formation pathways, and evolutionary histories of these objects.

The International Astronomical Union (IAU) adopted a working definition in 2003, later updated in 2018, according to which exoplanets are **objects below the deuterium-burning limit** (approximately 13 Jupiter masses for solar metallicity) **orbiting stars, brown dwarfs, or stellar remnants**, independently of their formation mechanism, while the **lower mass limit** is taken to be consistent with the definition adopted for planets in the Solar System.

Throughout this thesis, the term **exoplanet** refers to planetary companions satisfying the current IAU working definition, with particular emphasis on close-in giant planets characterized through complementary observational techniques.

2.1.2 Key Planetary Parameters

The physical characterization of an exoplanet hinges on the measurement of a few fundamental parameters. The most crucial of these are its mass (M_p) and radius (R_p). When combined, they yield the mean density, which provides the first clues about its bulk composition (e.g., rocky, gaseous, or icy). These bulk properties are governed by the planet’s orbital elements, such as the semi-major axis, eccentricity, and inclination, which define its trajectory around the host star.

For a more detailed understanding, particularly of giant planets, the study of their atmospheres is essential. Since the first detection of an atomic species in the atmosphere of HD 209458 b (Charbonneau et al., 2002), atmospheric spectroscopy has become a key tool for probing composition, thermal structure, and formation history (Seager and Deming, 2010; Madhusudhan, 2019). However, no single observational technique can constrain all of these properties simultaneously. Instead, a comprehensive physical characterization relies on combining complementary observations, where transit photometry, radial velocity measurements, and atmospheric spectroscopy provide independent constraints on planetary structure, orbital architecture, and atmospheric properties.

The physical parameters introduced above cannot all be determined from a single observational technique. Instead, they are inferred by combining complementary methods, each of which constrains different aspects of the planetary system. The main observational techniques currently used for exoplanet detection and characterization will be introduced in the following section.

2.1.3 Observational methods for exoplanet detection

Since exoplanets are generally unresolved from their host stars, their physical properties must be inferred indirectly through complementary observational techniques. Different methods have been developed over the past three decades, with each one probing different aspects of planetary systems, providing independent constraints on planetary and orbital parameters as well as, in some cases, atmospheric properties. In consequence, a comprehensive characterization requires combining multiple observational approaches.

Among the different techniques to discover exoplanets, *Transit photometry* is currently the most productive one, and constitutes one of the two primary

observational methods employed throughout this thesis. A planetary transit occurs when a planet passes in front of its host star as seen from the observer, producing a periodic decrease in the observed stellar flux. The transit depth is approximately proportional to $(R_p/R_\star)^2$, allowing a direct determination of the planetary radius once the stellar radius is known. Beyond planet detection, transit observations provide access to several fundamental orbital parameters, including the orbital period, inclination, scaled semi-major axis, and transit ephemeris. When combined with stellar models, transit light curves also constrain the stellar density, making transit photometry a cornerstone for the physical characterization of planetary systems.

Transit observations also enable atmospheric characterization through transmission spectroscopy. During transit, a small fraction of the stellar light filters through the planetary atmosphere before reaching the observer. Because atmospheric opacity varies with wavelength, the effective planetary radius becomes wavelength dependent, producing the transmission spectrum. Measurements of this spectrum provide constraints on atmospheric composition, scattering processes, cloud properties, and the presence of atomic or molecular absorbers such as Na I and K I, which constitute the primary focus of Chapter 4.

The large photometric precision achieved by dedicated space missions such as Kepler and NASA's *Transiting Exoplanet Survey Satellite* (*TESS*, [Ricker et al. 2014](#)) has transformed transit photometry into the dominant exoplanet detection technique, providing thousands of confirmed planets together with high-quality light curves suitable for detailed physical characterization.

Radial velocity (RV) measurements constitute the second primary observational technique employed throughout this thesis. Rather than observing the planet directly, the method measures the reflex motion of the host star induced by the gravitational pull of an orbiting companion. This motion produces periodic Doppler shifts in the stellar absorption lines, allowing the stellar radial velocity to be measured with high precision ([Lindgren and Dravins, 2003](#)).

This technique constrain the orbital period, eccentricity, argument of periastron, and the velocity semi-amplitude of the stellar motion. Combined with the stellar mass, these measurements yield the planetary minimum mass ($M_p \sin i$).

Furthermore, when transit photometry is also available, the orbital inclination is independently determined, removing the $\sin i$ degeneracy, thus allowing the true planetary mass M_p to be measured. Therefore, RV measurements play a dual role in modern exoplanet studies. They confirm the planetary nature of transit candidates while providing accurate mass determinations, which, when combined with transit-derived radii, yield the planetary bulk density. These quantities constitute the basis for interpreting planetary structure and atmospheric properties.

Several high-resolution spectrographs currently achieve sub-meter-per-second radial velocity precision, including the Keck Planet Finder (KPF, [Gibson et al. 2016](#)) and the High Accuracy Radial velocity Planet Searcher (HARPS, [Mayor et al. 2003](#)). In particular, HARPS provides the spectroscopic observations analyzed in this thesis and is introduced in more detail in Section 2.4.

It is worth noting that the detection of a transit-like or radial-velocity signal does not, by itself, guarantee the planetary nature of the candidate. Astrophysical false positives, such as eclipsing binary systems or blended stellar configurations, can produce signals that mimic those expected from transiting planets. Candidate validation therefore requires additional observational or statistical constraints to assess the probability that the detected signal is caused by a planet rather than by a false-positive scenario. Depending on the available data, this can involve complementary photometric and spectroscopic observations, high-resolution imaging, or statistical validation methods (e.g. VESPA, [Morton, 2012](#)) that estimate the false-positive probability. Such procedures are particularly important for large-scale transit surveys, where the identification of planetary candidates is followed by a process of confirmation or validation before their physical properties are adopted for further analysis. In the context of transit surveys, statistical validation can therefore provide an important complement to subsequent spectroscopic confirmation, particularly when assessing whether a transit signal is consistent with a planetary companion.

Other observational methods, including *gravitational microlensing*, *astrometry*, and *direct imaging*, probe complementary regions of the exoplanet parameter space. In particular, microlensing is sensitive to planets at several astronomical units from their host stars, while astrometry measures the reflex motion of the star on the

plane of the sky, and direct imaging enables the study of widely separated young giant planets. Although these techniques have produced important discoveries, they are not employed in the present work.

The present thesis combines transit photometry, high-precision radial velocity observations, and transmission spectroscopy to characterize giant planets. These complementary techniques constitute the observational framework adopted throughout the work presented in Chapters 4 and 5. Section 2.4 introduces the major surveys and facilities that provide the data analyzed in this thesis.

2.2 Exoplanet populations and classification

The large diversity of known exoplanets has motivated several classification schemes, mainly based on planetary radius and mass, providing a first-order indication of internal composition and physical structure. Figure 2.2.1 illustrates a summary of each of these four groups along their general characteristics. Although these categories represent a continuum rather than sharply defined classes, they offer a useful framework for interpreting planetary populations. Since this thesis focuses on giant planets, this section briefly introduces the main classes before discussing Hot Jupiters in detail.

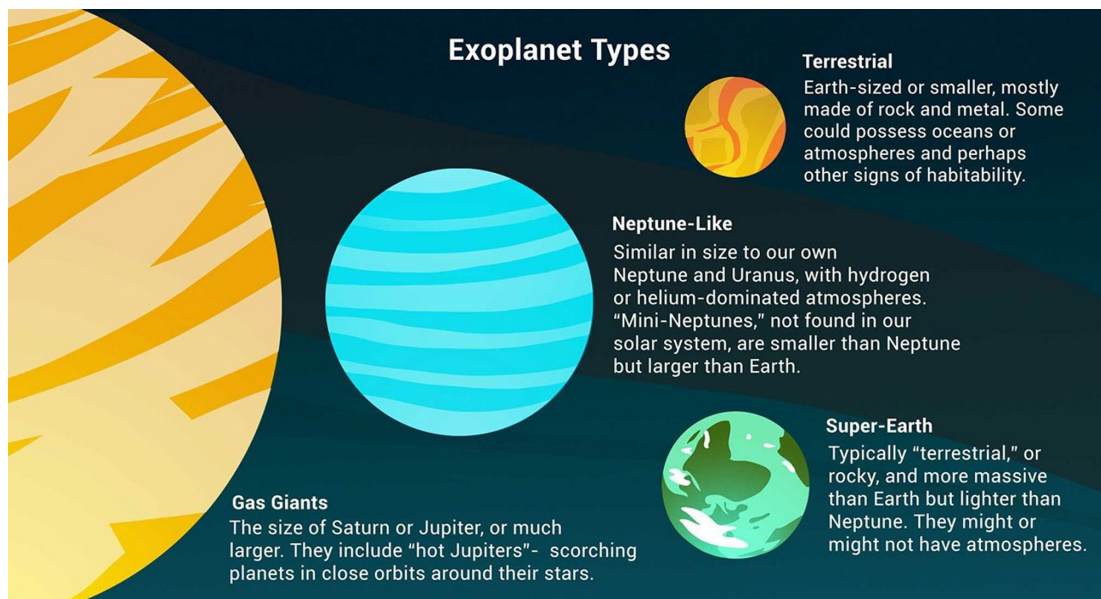


Figure 2.2.1: Illustration presenting the main types of exoplanets along their main physical characteristic. Credits: NASA/JPL-Caltech

Terrestrial planets are the *smallest known class of exoplanets* and are characterized by predominantly *rocky compositions* with relatively high bulk densities. Their radii are typically comparable to or smaller than that of the Earth, and several systems, such as TRAPPIST-1, have revealed that rocky planets may also host atmospheres and volatile reservoirs under suitable conditions (Grimm et al., 2018). Although terrestrial planets are primary targets in the search for potentially habitable worlds, they are not considered further in this thesis.

Super-Earths occupy the *transition between Earth-sized planets and Neptune-like planets*, generally spanning masses up to approximately 10 Earth masses. Although, despite their name, they do not necessarily resemble the Earth in either composition or habitability. Instead, they comprise a *heterogeneous population* ranging from predominantly rocky planets to volatile-rich objects. The absence of this type of planet in the Solar System makes them particularly important for comparative exoplanet studies, since there are still uncertainties regarding their true nature.

Neptune-like planets represent an intermediate population ($R_p \sim 4 R_\oplus$; $M_p \sim 17 M_\oplus$) characterized by hydrogen- and helium-rich envelopes surrounding more compact interiors. Their atmospheric properties have become increasingly accessible through transmission spectroscopy and observations with James Webb Space Telescope (JWST, Gardner et al., 2006), although clouds and hazes often obscure molecular and atomic absorption features. These planets provide valuable insight into the transition between terrestrial planets and gas giants.

Gas giant planets are those with sizes comparable to Saturn and Jupiter, or even larger. They are dominated by extended hydrogen- and helium-rich atmospheres surrounding more compact interiors. Their large radii, relatively high masses, and extended atmospheres produce deep transit signals and measurable stellar radial velocity variations, making them among the most favorable targets for detailed physical characterization. In particular, their large atmospheric scale heights enhance spectroscopic signatures during planetary transits, allowing atmospheric composition and structure to be investigated through transmission spectroscopy.

Among gas giant planets, Hot Jupiters (HJ), which were among the first type of exoplanets found, constitute one of the best-characterized exoplanet populations. Their short orbital periods maximize the probability of transit detection, while

their strong gravitational influence on their host stars enables precise radial velocity measurements. At the same time, their inflated and highly irradiated atmospheres make them ideal laboratories for atmospheric spectroscopy. These observational advantages have established Hot Jupiters as benchmark objects for investigating planetary structure, atmospheric physics, and formation processes. Consequently, they constitute the primary focus of this work and are discussed in detail in the following section.

2.3 Hot Jupiters

2.3.1 General description of hot Jupiters

Hot Jupiters (HJs) are giant gaseous planets with masses typically larger than $\sim 0.1 M_J$ and orbital periods shorter than about 10 days. Their close-in orbits expose them to intense stellar irradiation, producing equilibrium temperatures of several thousand kelvin and atmospheric conditions unlike those found in any planet of the Solar System. Owing to their short orbital periods, large radii, and strong gravitational influence on their host stars, HJs produce deep transit signals and measurable radial velocity variations, making them among the most favorable exoplanets for detailed physical characterization (Heng and Showman, 2015).

These observational advantages have established HJs as benchmark objects for investigating planetary structure, atmospheric physics, and orbital evolution. Their extended atmospheres produce large transmission spectroscopy signals, while the combination of transit photometry and radial velocity measurements enables accurate determinations of planetary radii, masses, and bulk densities. These quantities constitute the fundamental observational constraints required to interpret planetary atmospheres, investigate inflation mechanisms, and place giant planets within the broader context of planetary formation and evolution, which will be presented in the following sections. Consequently, HJs have become one of the best-characterized exoplanet populations and provide an ideal laboratory for studying the interplay between planetary interiors, atmospheres, and migration processes.

A particularly important subclass of these giant planets is the Ultra-Hot Jupiters (UHJs), which are commonly defined as HJ planets with equilibrium

temperatures above ~ 2000 K. Under these extreme conditions, molecular dissociation, thermal ionization, and strong day–night temperature contrasts give rise to atmospheric processes not observed in cooler giant planets. As a result, UHJs extend the physical regime explored by classical HJs, serving as natural laboratories for probing the limits of planet formation and providing valuable constraints on atmospheric chemistry, heat transport, and planetary evolution (e.g., Madhusudhan et al., 2011; Parmentier et al., 2018; Demangeon et al., 2024; Tan et al., 2024; Saha and Jenkins, 2025, 2026). Despite occupying the extreme end of the known exoplanet parameter space in terms of equilibrium temperature and radius, no clear correlation between these properties has been established to date, complicating efforts to constrain their formation pathways and leaving several fundamental questions open, including the dominant formation mechanisms of UHJs, whether their orbital eccentricities are consistent with current migration scenarios, and whether UHJs and classical HJs constitute distinct populations based on their atmospheric compositions and thermal structures (e.g., Helling et al., 2019; Fortney et al., 2021; Changeat and Edwards, 2021; Huang et al., 2023).

2.3.2 Formation theories for hot Jupiters

The presence of hot Jupiters (HJs) on short-period orbits raises the question of how these planets formed and reached their present-day configurations. Their proximity to their host stars is difficult to reconcile with standard planet formation scenarios. Consequently, several formation and migration pathways have been proposed to explain the origin of close-in giant planets.

Three main classes of scenarios are commonly considered:

1. **In-situ formation:** In this scenario, giant planets form close to their current orbital locations. This would require either gravitational instability (e.g., Boss, 1997; Durisen et al., 2007) or core accretion (Chabrier et al., 2014) to operate efficiently in the inner regions of the protoplanetary disk. However, both mechanisms face significant challenges under standard disk conditions (e.g., Rafikov, 2005, 2006), making in-situ formation a subject of ongoing theoretical debate.
2. **Disk migration:** In this scenario, giant planets form at larger orbital

distances and subsequently migrate inward through interactions with the protoplanetary disk. Planet–disk interactions can efficiently reduce the planetary semi-major axis while generally maintaining relatively low orbital eccentricities (Goldreich and Sari, 2003; Tsang et al., 2014; Duffell and Chiang, 2015). This mechanism therefore provides a natural explanation for the short orbital periods observed in many HJs, particularly for systems with nearly circular orbits.

3. **High-eccentricity tidal migration:** Dynamical interactions with additional companions, such as other planets or stellar companions, can excite a giant planet onto a highly eccentric orbit. During subsequent close passages to the host star, tidal dissipation removes orbital energy and progressively circularizes the orbit, resulting in a short period configuration (Dawson and Johnson, 2018). The existence of highly eccentric giant planets, such as HD 80606 b ($e = 0.93$; Naef et al. 2001), provides observational evidence for the dynamical processes involved in this class of migration scenarios.

An illustrative view of these formation and migration pathways is shown in Figure 2.3.1.

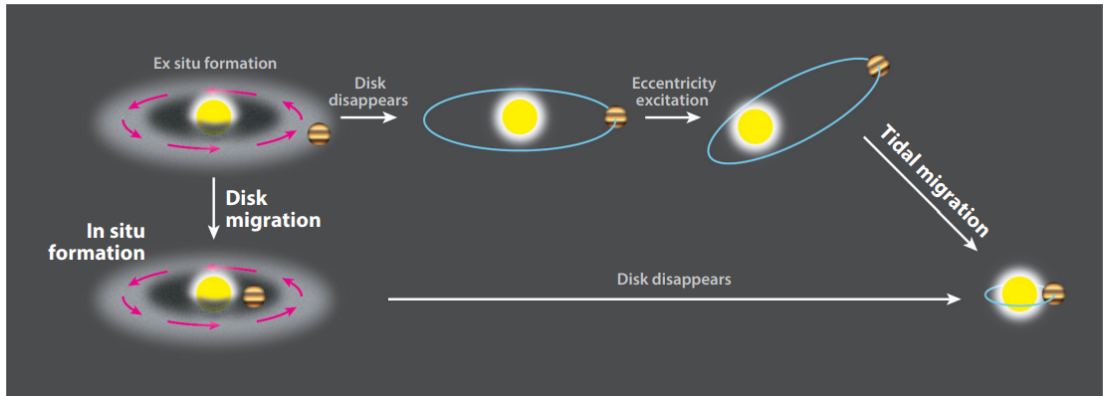


Figure 2.3.1: Illustrative view of hot Jupiter formation scenarios. Credits: Dawson and Johnson (2018).

Although distinguishing between these scenarios observationally remains challenging, each pathway predicts different orbital and planetary properties. In particular, orbital eccentricity and spin–orbit alignment can provide clues about the dynamical history of a planetary system, while atmospheric composition may retain information about the environment in which the planet formed and the

material it subsequently accreted.

The chemical composition of a protoplanetary disk varies with orbital distance as different species condense at different temperatures. Consequently, the location where a giant planet forms, together with the gas and solids accreted during its growth and migration, can influence its atmospheric elemental abundances, including the C/O ratio and metallicity (Öberg et al., 2011; Madhusudhan et al., 2014b). Atmospheric characterization can therefore provide complementary constraints on formation and migration scenarios, although interpreting these signatures is not straightforward because different evolutionary pathways can produce similar atmospheric compositions (Penzlin et al., 2024).

2.3.3 The Radius Inflation problem in hot Jupiters

Standard evolutionary models predict that gas giant planets cool and contract over time after their formation (e.g., Pollack et al., 1996; Fortney et al., 2021). For hot Jupiters, however, a significant fraction of the observed radii are larger than predicted by standard evolutionary models, giving rise to the *radius inflation problem*. The magnitude of this discrepancy can be substantial, with some highly irradiated giant planets exhibiting radii 20–50% larger than expected for their mass and evolutionary state, particularly for HJs with masses comparable to that of Jupiter (Thorngren and Fortney, 2018; Thorngren, 2024).

Figure 2.3.2 illustrates the observed radius distribution of giant exoplanets with masses between 0.1 and $13 M_{\text{Jup}}$ as a function of incident stellar flux, with the red-dashed line showing the evolutionary model for planets without inflation. The increase in planetary radius with increasing irradiation provides strong observational evidence for a connection between stellar energy input and the inflated radii of close-in giant planets (Thorngren and Fortney, 2018). However, the physical processes through which incident stellar energy can affect the deep planetary interior remain uncertain.

Several mechanisms have been proposed to explain radius inflation, which can be broadly grouped into two classes:

1. **Additional energy deposition:** mechanisms in which a fraction of the stellar or orbital energy is deposited into the planetary interior, such as tidal heating associated with orbital eccentricity (Dawson and Johnson, 2018)

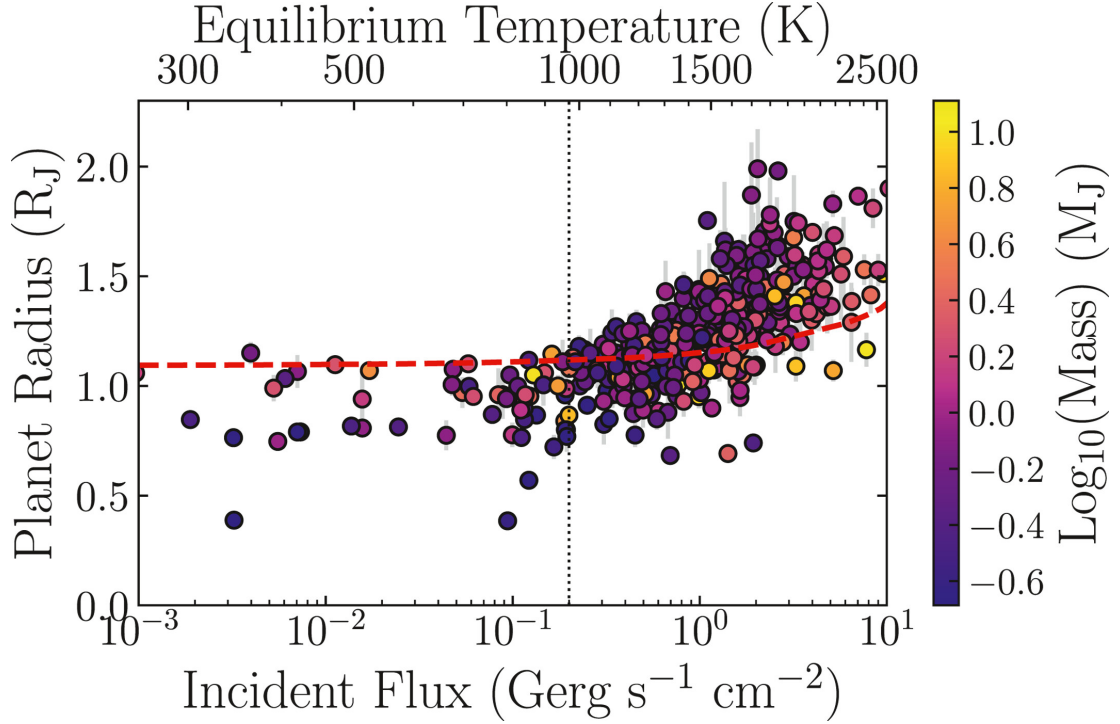


Figure 2.3.2: Observed radius of extrasolar gas giants between $0.1 - 13 M_{\text{Jup}}$, plotted as a function of incident stellar flux and colored by planetary mass. Credits: Fortney et al. (2021), adapted from Thorngren and Fortney (2018).

and ohmic dissipation resulting from atmospheric winds interacting with the planetary magnetic field (Batygin and Stevenson, 2010).

2. **Delayed cooling:** mechanisms that reduce the efficiency with which a planet loses its internal energy, for example through enhanced atmospheric opacity associated with high metallicity or clouds, thereby slowing planetary contraction (Miller and Fortney, 2011).

Despite extensive theoretical and observational efforts, no single mechanism has been established as the dominant explanation for the observed population of inflated hot Jupiters, and multiple processes may contribute to the phenomenon (Thorngren, 2024).

The connection between irradiation, atmospheric structure, and planetary evolution makes atmospheric characterization particularly relevant to the study of radius inflation. Atmospheric composition, opacity, and thermal structure influence the transport and redistribution of energy within irradiated planets, and may therefore provide constraints on the physical processes involved in their long-term evolution. Nevertheless, the relationship between atmospheric properties

and radius inflation remains complex, and atmospheric observations alone cannot identify a unique inflation mechanism.

In this thesis, the transmission spectrum of TOI-1019 b provides constraints on its atmospheric composition and scattering properties. These results contribute to the characterization of irradiated giant planets and to the broader understanding of the atmospheric diversity observed among hot Jupiters.

2.3.4 Atmospheric studies of hot Jupiters

The study of hot Jupiter atmospheres provides a key observational window into their formation history and physical evolution. Their large radii, high equilibrium temperatures, and extended atmospheres result in large atmospheric scale heights H and enhanced spectroscopic signals, making them particularly favorable targets for atmospheric characterization. Transmission spectroscopy is especially well suited to these planets, as wavelength-dependent transit depths can be used to probe their atmospheric composition and structure.

For a typical giant planet with a mass and radius comparable to those of Jupiter, the atmospheric scale height is of the order of a few hundred kilometers, producing wavelength-dependent variations in the transit depth that can reach the level of a few hundredths to tenths of a percent, depending on the properties of the planetary and host stars. The effective optical radius of a planet generally varies with wavelength, $R_p(\lambda)$, and this wavelength dependence constitutes the transmission spectrum. Transmission spectra can reveal absorption signatures from atomic and molecular species (see, e.g., [Seager and Deming, 2010](#), for a review), providing constraints on atmospheric composition and chemical enrichment. Atomic species have been detected in the UV and optical transmission spectra of hot Jupiters, including Na I and K I, which produce prominent features near 589 and 770 nm, respectively ([Charbonneau et al., 2002](#); [Fortney et al., 2021](#)). Scattering by aerosols or haze particles can also be inferred from the wavelength dependence of the planetary radius, particularly through spectral slopes at short wavelengths ([Sing et al., 2011](#)). When Rayleigh scattering is assumed to be the dominant contributor to the wavelength dependence of $R_p(\lambda)$, [Lecavelier Des Etangs et al. \(2008b\)](#) showed that the effective transit depth δ at a given wavelength λ can be expressed as

$$\delta = \delta_0 \left(1 - \frac{8H}{R_p} \ln \frac{\lambda}{\lambda_0} \right) \quad (2.3.1)$$

where δ_0 is the transit depth measured at a reference wavelength λ_0 where scattering is negligible (e.g., in a red or IR band, as Rayleigh-scattering is proportional to λ^{-4}). Thus, measurements of the wavelength dependence of $R_p(\lambda)$ can provide constraints on the atmospheric scale height H and, under assumptions about the atmospheric temperature and composition, on the mean molecular weight μ (Lecavelier Des Etangs et al., 2008a). Combined with atmospheric retrieval models (e.g., Nascimbeni et al., 2013; Al-Refaie et al., 2021, 2022), transmission spectra can therefore be used to constrain the abundances of atmospheric species and other properties such as atmospheric metallicity and cloud or haze properties.

Observations of hot Jupiter atmospheres have revealed a remarkable diversity in their physical and chemical properties. Some planets exhibit relatively clear atmospheres with prominent absorption features from atomic species such as Na I and K I (e.g., Charbonneau et al., 2002; Snellen et al., 2008; Sing et al., 2011; Nikolov et al., 2014; Sing et al., 2015; Nikolov et al., 2016; Sing et al., 2016; Sedaghati et al., 2016; Chen et al., 2018; Oshagh et al., 2020), while scattering processes can produce Rayleigh-like slopes at blue wavelengths (Jordán et al., 2013; Palle et al., 2017). In contrast, many hot Jupiters exhibit muted or apparently featureless transmission spectra, which may result from clouds and hazes obscuring the underlying atomic and molecular signatures. This diversity highlights the difficulty of uniquely interpreting transmission spectra, since similar spectral features can arise from different combinations of atmospheric composition, temperature structure, cloud and haze properties, and planetary radius.

The interpretation of transmission spectra is further complicated by the properties of the host star. Stellar activity, including unocculted spots and faculae, can modify the observed transit depth in a wavelength-dependent manner and introduce spectral slopes or other features that may be incorrectly attributed to the planetary atmosphere (e.g., Sing et al., 2011; Rackham et al., 2019). Consequently, reliable atmospheric characterization requires consideration of both planetary and stellar contributions to the observed spectrum. These effects are particularly important for transmission spectroscopy, where the atmospheric signal is typically small compared with the total stellar flux (Rackham et al., 2019, 2023).

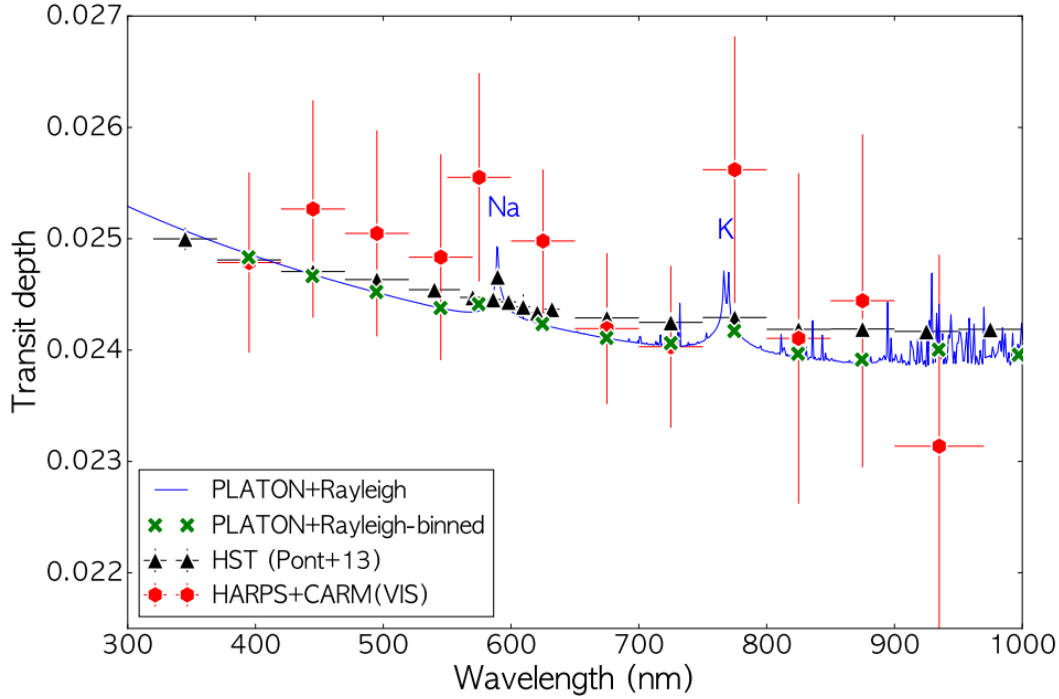


Figure 2.3.3: Transmission spectrum of HD 189733b, illustrating wavelength-dependent transit depths and absorption features associated with atomic species such as Na I and K I. Credits: [Oshagh et al. \(2020\)](#).

Accurate knowledge of the planetary mass is also important for interpreting transmission spectra. The planetary mass, together with the radius, determines the surface gravity and therefore contributes directly to the expected atmospheric scale height. Radial velocity measurements provide an independent constraint on the planetary mass and, when combined with transit observations, allow the atmospheric signal to be interpreted within a better-constrained physical framework (e.g., [Di Maio et al., 2023](#)). Conversely, under appropriate assumptions, the pressure-dependent structure of a transmission spectrum can also be used to constrain the planetary mass from atmospheric observations, as demonstrated by the *MassSpec* approach of [de Wit and Seager \(2013\)](#). Accurate planetary masses are therefore valuable not only for determining the bulk properties of hot Jupiters, but also for reducing uncertainties in the interpretation of their atmospheric spectra and in assessing their evolutionary properties.

Beyond their atmospheric properties themselves, transmission spectra can provide information relevant to the formation and evolutionary history of hot Jupiters. The composition of gas and solids in protoplanetary disks varies with radial distance

as the disk temperature decreases and volatile species condense at different snow lines (e.g., [Öberg et al., 2011](#)). Consequently, atmospheric elemental abundances, including ratios such as C/O and overall metallicity, may retain information about the material accreted during planetary formation and subsequent migration (e.g., [Madhusudhan et al., 2014a,b](#)). In particular, a HJ formed in situ would be expected to acquire a composition characteristic of the inner disk, where relatively few ices can condense, whereas a planet undergoing high-eccentricity tidal migration could retain signatures of material accreted at larger orbital distances. If disk migration is the dominant migration pathway, the planet may instead acquire an intermediate composition by accreting material at different locations as it migrates through the disk (e.g., [Alibert et al., 2005](#)). However, interpreting atmospheric abundances in terms of a specific formation pathway is not straightforward, since the observed composition can also be modified by processes occurring during accretion and subsequent planetary evolution.

Despite the large number of known hot Jupiters, only a subset currently possesses sufficiently precise and informative atmospheric observations to constrain their atmospheric properties in detail. Transmission spectroscopy therefore remains an important, but intrinsically model-dependent, tool for studying irradiated giant planets. Its interpretation is strengthened when combined with complementary constraints on planetary mass, radius, stellar properties, and orbital parameters, which help reduce degeneracies between atmospheric and planetary properties.

In this thesis, transmission spectroscopy is used to constrain the atmospheric properties of TOI-1019 b. By combining spectrophotometric observations with atmospheric modeling, this study places the target within the broader population of hot Jupiter atmospheres and contributes to the characterization of irradiated giant planets and their atmospheric diversity.

2.4 Major surveys and facilities for exoplanet characterization

The rapid development of exoplanet science has been driven by dedicated photometric surveys and high-resolution spectroscopic facilities, which together enable the detection and physical characterization of planetary systems. Space-based transit missions identify planetary candidates through high-precision

photometry, whereas ground-based spectrographs provide the radial velocity measurements required to determine planetary masses and confirm their planetary nature. Together, these complementary observations can enable a complete physical characterization of planetary systems.

The present thesis combines observations from some of these complementary facilities. Transit photometry from the *Transiting Exoplanet Survey Satellite* (*TESS*) is used to detect and characterize planetary transits, while high-resolution spectra obtained with the High Accuracy Radial velocity Planet Searcher (HARPS) provide the radial velocity measurements required to determine planetary masses. In addition, transmission spectroscopy is employed to investigate atmospheric properties. This section briefly introduces the main facilities that have established this observational framework.

Although several space missions have contributed significantly to exoplanet science, only a subset is directly relevant to this thesis. Earlier missions such as *Kepler* demonstrated the ubiquity of planetary systems through long-duration photometric monitoring, while infrared observatories such as *Spitzer* pioneered atmospheric studies of transiting planets. Current and future facilities, including *TESS*, HARPS, and the upcoming PLATO mission (Rauer et al., 2025), extend these capabilities toward the discovery and characterization of planets orbiting bright nearby stars.

Figure 2.4.1 summarizes the evolution of major exoplanet missions over the past decades.

2.4.1 The Kepler Space Telescope and K2 Missions

Kepler was NASA’s first mission dedicated to the discovery of exoplanets, launched on March 6, 2009. It was tasked to search for Earth-sized exoplanets in the habitable zones of their host stars, in a portion of the Milky Way galaxy, through continuous high-precision photometric monitoring of more than 150,000 stars (Borucki et al., 2010). Kepler was specifically designed to determine the occurrence rate of planets through continuous high-precision transit photometry.

By detecting periodic transit signals, Kepler demonstrated that planetary systems are common throughout the Galaxy, revealing an extraordinary diversity of planetary architectures. Beyond discovering thousands of planetary candidates,



Figure 2.4.1: Overview of major past, current, and future exoplanet missions as of 2022. Credit: NASA.

Kepler established the statistical foundations of modern exoplanet population studies, including the occurrence rates of small planets and the identification of population features such as the *radius valley* (Fulton et al., 2017). The diversity of the exoplanet population revealed by these surveys is illustrated in Figure 2.4.2. Following the failure of two reaction wheels, the mission continued as the K2 survey, extending its scientific impact until 2018.

Although Kepler observations are not analyzed in this thesis, the mission established the observational and statistical framework of modern transit surveys. Its success directly motivated the development of all-sky missions such as *TESS*, which provides the photometric observations analyzed throughout this work.

2.4.2 The *TESS* Mission

The Transiting Exoplanet Survey Satellite (*TESS*, Ricker et al., 2014) is a currently ongoing MIT-led NASA mission, launched in April 20, 2018. It was designed to conduct an all-sky survey for transiting exoplanets, with particular emphasis on planets smaller than Neptune orbiting bright stars suitable for spectroscopic follow-up observations that can provide atmospheric compositions. *TESS* surveys

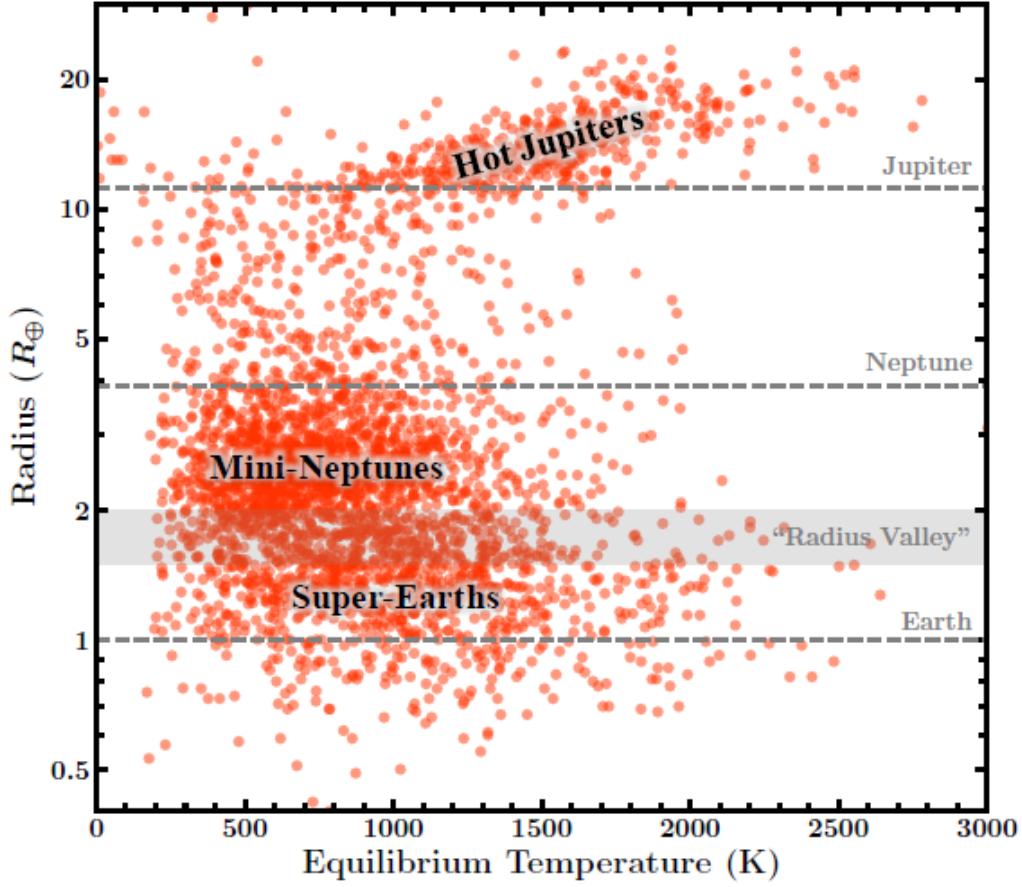


Figure 2.4.2: Distribution of confirmed exoplanets in the radius–equilibrium temperature plane. The shaded region indicates the *radius valley* separating super-Earths from sub-Neptunes. Credits: NASA Exoplanet Archive: <https://exoplanetarchive.ipac.caltech.edu>

the sky in series of 27-days long observing sectors (see Figure 2.4.3).

Since its launch in 2018, including its extended mission in 2020, *TESS* has detected thousands of planet candidates, providing an extensive archive of light curves, which are analyzed with the Science Processing Operations Center (SPOC, Jenkins et al., 2016), and the most prominent targets with transit-like signals are classified as *TESS Objects of Interest* (TOIs, Guerrero et al., 2021; Huang et al., 2020a), which constitute the starting point for subsequent confirmation and characterization studies. *TESS* has become one of the main drivers of modern exoplanet research, providing thousands of planet candidates and hundreds of confirmed planets across a broad range of stellar and planetary properties. Its continuous stream of discoveries has established it as the principal source of targets

for atmospheric studies and high-precision radial velocity follow-up.

TESS constitutes the primary photometric facility used throughout this thesis, providing the initial photometric data and identifying the transiting signals of all three planet analyzed in Chapters 4 and 5. Chapter 3 describes the methodology employed to process and analyze the photometric data obtained from *TESS*, focusing on transit detection and characterization of the three objects. Consequently, *TESS* forms the observational basis of the photometric analysis developed in this work.

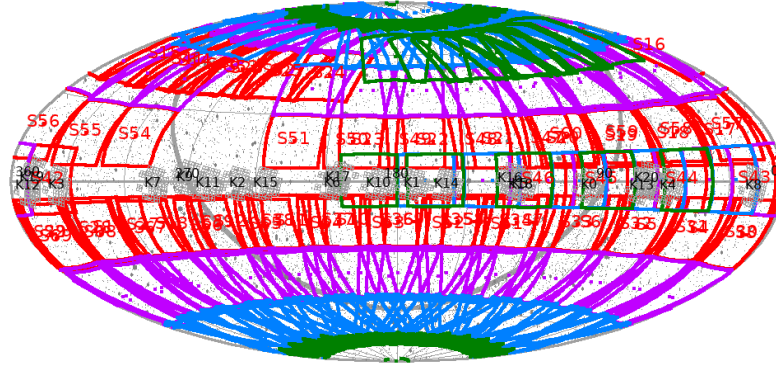


Figure 2.4.3: Overlay of *TESS* Year 1-7 pointings in ecliptic coordinates displaying all observed Sectors. Credits: *TESS* official website¹.

2.4.3 The HARPS spectrograph

The High Accuracy Radial Velocity Planet Searcher (HARPS, [Mayor et al., 2003](#)) is a high-precision echelle planet-finding spectrograph installed in 2002 on the ESO's 3.6m telescope at La Silla Observatory, Chile. This instrument is designed to obtain high long-term measurements of radial velocities, achieving RV measurements up to the order of 1 m/s, making it one of the most successful instruments for exoplanet confirmation and mass determination.

Owing to its long-term instrumental stability and sub-meter-per-second high-precision RV measurements, HARPS has become one of the reference instruments for confirming planetary candidates discovered by transit surveys and for measuring precise planetary masses, as explained in Section 2.1.3. When combined with transit photometry, these measurements yield the planetary bulk density, providing fundamental constraints on the internal structure of exoplanets and thereby providing the fundamental physical quantities required for atmospheric

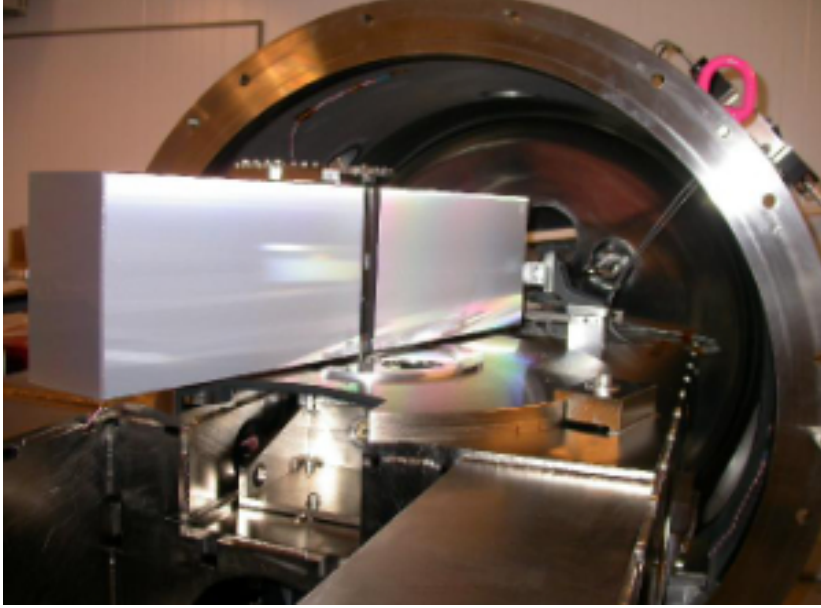


Figure 2.4.4: Photography of HARPS. Credits: ESO.

characterization.

HARPS provides the spectroscopic observations analyzed throughout this thesis. In particular, the radial velocity measurements presented in Chapter 5 are used to confirm the planetary nature of two systems and determine their masses, complementing the *TESS* transit observations used to derive their radii. The data reduction and analysis procedures adopted for the HARPS observations are described in Chapter 3.

2.4.4 The PLATO mission

The European Space Agency’s PLAnetary Transits and Oscillations of stars (PLATO, [Rauer et al. 2025](#)) mission is the next major space mission dedicated to the detection and characterization of transiting exoplanets around bright stars. Currently scheduled for launch in 2027, PLATO will combine long-duration high-precision photometry (up to two-years of continuous observation) with asteroseismology to determine both planetary and stellar properties with unprecedented accuracy.

For this thesis, the PLATO mission provides an important perspective for future studies. In particular, two of the planetary systems analyzed in Chapter 5 are located within one of the Long Observation Phase fields (LOPS2, [Nascimbeni](#)

et al. 2025), making them potential targets for future PLATO observations. Such observations would provide higher-precision transit photometry over much longer temporal baselines than currently available, improving orbital ephemerides and planetary parameters while enabling detailed studies of transit timing variations, stellar variability, and long-term system evolution.

2.4.5 The Spitzer Space Telescope Mission

The Spitzer Space Telescope (Werner et al., 2004) was the fourth and last of NASA’s *Great Observatories Projects* launched in August 25, 2003, it managed to observe the sky for almost 17 years. Spitzer pioneered infrared observations of exoplanet atmospheres and provided some of the first measurements of thermal emission and atmospheric properties of transiting planets.

Among its most relevant exoplanet discoveries, using the transit photometry and gravitational microlensing techniques, its the finding of the Trappist-1 system (Section 2.2)., as well as the discovery of HD 219134 b, a rocky planet with a three-day orbit around its star, in 2015.

Although its observations have played a fundamental role in atmospheric characterization, Spitzer data are not used in this thesis. Nevertheless, its pioneering infrared observations established many of the observational techniques that are now routinely employed for atmospheric characterization of transiting giant planets.

Chapter 3

Methodology

This chapter describes the observational and analytical methodology employed to characterize the giant exoplanets studied in this thesis. The procedures include the acquisition and reduction of spectrophotometric observations with IMACS and high-precision radial velocity observations with HARPS, the construction and analysis of transmission spectra, and the subsequent modeling of photometric, spectrophotometric, and radial velocity datasets using specialized astronomical software and statistical methods. The methodology is presented with emphasis on the procedures and assumptions relevant to the analyses developed in Chapters 4 and 5, while detailed target-specific results and their scientific interpretation are presented in the corresponding chapters.

3.1 Observations with IMACS

The Inamori-Magellan Areal Camera & Spectrograph (IMACS, Dressler et al., 2011) is a multi-object spectrograph mounted on the 6.5 m Baade-Magellan Telescope at Las Campanas Observatory in Chile (Shectman and Johns, 2003). In this thesis, IMACS was used to obtain spectrophotometric observations of the hot Jupiter TOI-1019 b with the aim of constructing a low-resolution optical transmission spectrum.

The observations were performed using the $f/4$ camera in the Multi-Object Spectroscopy (MOS) configuration, which allows the target and reference stars to be observed simultaneously throughout the transit, together with a 300 line mm^{-1}

grating at a blaze angle of 4.3° , providing a wavelength coverage of approximately 400–950 nm. This spectral range includes prominent optical features of atomic species such as Na I and K I. I designed and prepared a custom MOS mask using `maskgen`¹, containing five $5'' \times 12''$ slits. One slit was assigned to TOI-1019, while the remaining slits were placed on reference stars with similar magnitudes and colors. Eight additional stars were used as guide stars for mask alignment and telescope pointing. The simultaneous observation of the target and reference stars enabled differential spectrophotometry and helped mitigate systematic effects affecting the relative flux measurements.

The reduced spectra were subsequently used to construct wavelength-dependent transit light curves and the resulting transmission spectrum, following the procedure described in Section 3.3. The specific observing conditions, exposure sequence, and target-dependent results obtained from the IMACS observations of TOI-1019 b are presented in the corresponding chapter.

3.2 Radial velocity observations with HARPS

The High Accuracy Radial velocity Planet Searcher (HARPS, Mayor et al., 2003) is a high-resolution, high-precision échelle spectrograph installed on ESO’s 3.6 m telescope at La Silla Observatory in Chile. In this thesis, HARPS was used to obtain high-precision radial velocity measurements of TOI-6105 and *Gaia*-7, providing the spectroscopic data required to constrain the masses and orbital properties of their planetary companions when combined with transit photometry.

The HARPS observations were prepared using ESO’s standard observing infrastructure. The observation sequences were defined through Observation Blocks (OBs) using the Phase 2 Proposal Preparation (P2PP) tools and executed at the telescope through the BOB system. The resulting raw data were subsequently transferred to the ESO data archive and processed through the standard HARPS Data Reduction Software (DRS). This workflow ensured that the observations were executed according to the predefined instrumental configuration and that the resulting data were processed consistently through the standard reduction pipeline.

The observations were conducted using the standard high-accuracy mode, with a $1''$

¹<https://code.obs.carnegiescience.edu/maskgen/mask-generation-software>

science fiber centered on the target and fiber B positioned on the sky (Mayor et al., 2003). This configuration provides high-precision radial velocity measurements while allowing the sky contribution to be monitored simultaneously.

The raw HARPS data were processed using the standard HARPS DRS, which performs the basic reduction and extraction of the spectra, wavelength calibration using the Th-Ar reference, and radial velocity determination through the cross-correlation function (CCF) method (Pepe et al., 2002, and references therein). In this procedure, the observed stellar spectrum is correlated with a numerical mask selected according to the approximate spectral type of the target star. For the targets analyzed in this thesis, a G2 mask was adopted. In addition to the radial velocity measurements, the DRS provides spectroscopic diagnostics related to stellar activity and line-profile variations, including the bisector inverse slope (BIS), the full width at half maximum (FWHM), and the equivalent width of the CCF (W_{CCF} ; see Collier Cameron et al., 2019).

To further characterize stellar activity, the chromospheric activity indices $\log R'_{\text{HK}}$ and $\text{H}\alpha$ were extracted from the reduced HARPS spectra using the ACTIN 2 code (Gomes da Silva et al., 2018, 2021). These activity indicators, together with the radial velocity measurements and the CCF diagnostics, were used to assess possible stellar contributions to the observed RV variations and to inform the subsequent dynamical modeling of TOI-6105 and *Gaia*-7 described in Section 3.4.2.

The resulting HARPS radial velocity time series and spectroscopic activity indicators constitute the primary spectroscopic dataset used in the analysis of TOI-6105 b and *Gaia*-7b presented in Chapter 5. The specific observations, temporal sampling, and target-dependent results are described in the corresponding chapter.

3.3 Transmission Spectroscopy

Transmission spectroscopy consists of measuring the wavelength dependence of the transit depth, or equivalently the effective planetary radius $R_p(\lambda)$, as a planet passes in front of its host star. Because different atmospheric species absorb radiation at different wavelengths, variations in the transit depth can be used to probe the atmospheric opacity along the planet’s day–night terminator and to identify or constrain the presence of atomic and molecular species, as well as aerosols and hazes (e.g. Madhusudhan et al., 2014b; Crossfield, 2015; Deming

and Seager, 2017; Kreidberg, 2018). The wavelength dependence of the planetary radius can also reveal scattering processes, such as Rayleigh scattering, through the presence of a spectral slope at short wavelengths (Sing et al., 2011).

For spectrophotometric observations such as those obtained with IMACS in this thesis, the transmission spectrum is constructed from wavelength-dependent transit light curves. The observed spectra are divided into a set of wavelength channels, and the flux within each channel is integrated to produce a chromatic light curve. These light curves are then modeled independently to determine the corresponding planet-to-star radius ratio $R_p/R_\star$ and transit depth for each wavelength channel. The resulting wavelength dependence of $R_p/R_\star$, or equivalently of the transit depth, constitutes the transmission spectrum. The specific construction and analysis of the chromatic light curves obtained for TOI-1019 b are presented in Chapter 4, while the general transit modeling procedure used to derive the wavelength-dependent planetary radii is described in Section 3.4.2.

The amplitude of atmospheric features in a transmission spectrum is related to the atmospheric scale height H . Under assumptions about the atmospheric temperature and composition, measurements of the wavelength dependence of $R_p(\lambda)$ can therefore provide constraints on the atmospheric scale height and, consequently, on the mean molecular weight μ (Lecavelier Des Etangs et al., 2008a). Conversely, if the atmospheric temperature and composition are constrained independently, the observed spectral amplitude can provide information on the atmospheric scale height.

The interpretation of transmission spectra can be further developed through the use of atmospheric forward and retrieval models (e.g. Nascimbeni et al., 2013; Al-Refaie et al., 2021, 2022). These models allow the observed transmission spectrum to be compared with theoretical atmospheric spectra in order to constrain atmospheric composition and other physical properties. In this thesis, the transmission spectrum obtained from the IMACS observations of TOI-1019 b was subsequently used as input for the atmospheric retrieval analysis described in Section 3.4.3.

3.4 Data analysis and modeling

In order to work with the raw data from IMACS and the reduced data from HARPS, as well as photometric data from *TESS* and ground-based photometric

observations (for the case of *Gaia*-7b), I made use of specialized astronomical software and packages. The following subsections provide a brief description of the role, key features, and application of the software and packages used in this work.

3.4.1 IRAF

The Image Reduction and Analysis Facility (IRAF) is a software system widely used for the reduction and analysis of astronomical data, particularly for CCD imaging and spectroscopy (Tody, 1986). In this work, I used IRAF to reduce the raw IMACS multi-object spectroscopic observations and obtain wavelength-calibrated one-dimensional spectra of TOI-1019 b and the reference stars.

The raw IMACS observations consist of separate images from the multiple CCDs that compose the instrument’s detector. I first used the `igapmos` task to combine the individual CCD images corresponding to each exposure into a single MOS image. This allowed the subsequent reduction to be performed on the complete multi-object field rather than independently on each CCD.

The resulting MOS images were then processed using the `ccdred` and `twodspec` packages in IRAF. The reduction included the following steps:

- **Bias subtraction:** An average bias frame was constructed from multiple bias exposures and subtracted from each science frame.
- **Flat-field correction:** Dome-flat exposures were used to correct for pixel-to-pixel sensitivity variations across the detector.
- **Cosmic-ray rejection:** Cosmic-ray events were identified and removed during the image-combination and reduction process with the `imcombine` task.
- **Spectral extraction:** The `apall` task was used to extract one-dimensional spectra from the two-dimensional MOS images for TOI-1019 b and each reference star.
- **Wavelength calibration:** He, Ne, and Ar arc-lamp exposures were used to determine the wavelength-dispersion solution, which was subsequently applied to the extracted science spectra.

The one-dimensional spectra obtained from the IRAF reduction showed small wavelength offsets between the target and reference-star spectra. To align the spectra onto a consistent wavelength scale, I developed and applied a Python script following guidance from my co-supervisor. The correction was defined using a set of prominent spectral lines identified across the observed wavelength range. For each target and reference star, wavelength shifts were interpolated between the selected reference lines and applied to the corresponding wavelength arrays, while preserving the measured fluxes. The resulting wavelength-aligned spectra were then used in the subsequent spectrophotometric analysis. Examples of the spectra before and after this wavelength alignment are provided in Appendix A5.1.

The final output of this process consisted of wavelength-calibrated and wavelength-aligned one-dimensional spectra for each exposure of the transit sequence. These spectra were subsequently used to construct the wavelength-dependent transit light curves and derive the transmission spectrum following the procedure described in Section 3.3.

3.4.2 PyORBIT

3.4.2.1 The PyORBIT package

PyORBIT (Malavolta, 2016) is a Python package designed for the Bayesian modeling of exoplanetary transits and radial-velocity (RV) observations. It allows multiple datasets to be modeled simultaneously within a common probabilistic framework, including planetary orbital signals, transit light curves, instrumental offsets, and additional noise or stellar-activity contributions when required by the data.

In this thesis, I used PyORBIT as the main tool for the joint analysis of the photometric and spectroscopic datasets. For TOI-1019 b, the analysis combined the *TESS* photometry with the chromatic light curves obtained from the IMACS spectrophotometric observations. For TOI-6105 b and *Gaia*-7b, the photometric datasets were modeled jointly with the available radial-velocity measurements. The preparation of the corresponding observational datasets is described in Sections 3.1, 3.2, and 3.3.

For the transit component, PyORBIT uses the BATMAN package to calculate the theoretical transit light curve for a given set of orbital and planetary parameters. In the analyses presented in this thesis, the transit model was parameterized

using the reference transit epoch, orbital period, impact parameter, and stellar density, together with the quadratic limb-darkening coefficients. For the radial-velocity datasets, the model additionally included the RV semi-amplitude and dataset-dependent velocity offsets and jitter terms. When testing non-circular orbital configurations, the orbital eccentricity and argument of periastron were also included. The treatment of limb darkening is described separately in Section 3.4.2.6.

The model parameters were constrained through Bayesian inference using Markov Chain Monte Carlo (MCMC) sampling implemented with `emcee`. An initial global optimization of the model parameters was performed using the differential evolution algorithm implemented in `PyDE`, followed by the MCMC sampling. The posterior distributions were obtained from the combination of the adopted parameter priors and the likelihood of the observed datasets, and were used to derive the corresponding parameter estimates and credible intervals.

3.4.2.2 Treatment of multiple datasets and noise

The `PyORBIT` framework allows different photometric and spectroscopic datasets to be modeled simultaneously while accounting for dataset-dependent nuisance parameters. In the analyses presented in this thesis, jitter terms were included to account for additional unmodeled scatter in the corresponding datasets. For the IMACS chromatic light curves of TOI-1019 b, correlated noise was additionally modeled using a Gaussian Process with a Matern 3/2 kernel (e.g., [Palle et al., 2020](#)), implemented through `celerite2` ([Foreman-Mackey et al., 2017](#); [Foreman-Mackey, 2018](#)).

3.4.2.3 Application to TOI-1019 b

For TOI-1019 b, the analysis was performed in two stages. First, the *TESS* photometric data were modeled to constrain the global transit and stellar parameters. The resulting posterior distributions were subsequently used to define the priors for the analysis of the chromatic light curves obtained from the IMACS observations. The stellar parameters were updated using the values obtained from the stellar characterization, while wavelength-dependent limb-darkening coefficients were adopted for each IMACS spectral channel. The `PyORBIT` analysis was then performed independently for each of the 13 final spectral channels, yielding

a transit depth and a corresponding best-fit transit model for each channel. The resulting transit depths and planet-to-star radius ratios were subsequently used to characterize the wavelength dependence of the transit signal.

3.4.2.4 Application to TOI-6105 b and *Gaia*-7b

For TOI-6105 b and *Gaia*-7b, PyORBIT was used to jointly model the available transit photometry and radial-velocity measurements. The photometric data constrain the transit geometry and planetary radius, while the radial velocities provide the information required to constrain the orbital motion and planetary mass. Two orbital configurations were considered in the analysis, assuming either a circular orbit or an eccentric Keplerian orbit, as detailed in Chapter 5, Section 5.5.3.

3.4.2.5 The *BASic Transit Model cAlculationN* code

The *BASic Transit Model cAlculationN* (BATMAN) code (Kreidberg, 2015) is a Python package that computes analytical transit light curves based on the formalism of Mandel and Agol (2002). In this thesis, BATMAN was used within the PyORBIT framework to calculate the transit component of the likelihood model.

For a given set of orbital and planetary parameters, BATMAN computes the relative stellar flux during transit. A quadratic limb-darkening law was adopted, with the corresponding coefficients constrained using the PyLDTk calculations described in Section 3.4.2.6. For the IMACS spectrophotometric analysis, the transit model was evaluated independently for each spectral channel using the corresponding observation times and limb-darkening coefficients.

To account for the finite integration time of the observations, the transit models were evaluated using the exposure times and supersampling factors adopted for each dataset. The oversampled model was subsequently averaged to obtain the model flux corresponding to the effective observation time.

3.4.2.6 The PyLDTk package

PyLDTk (Husser et al., 2013; Parviainen and Aigrain, 2015) is a Python package that computes stellar limb-darkening coefficients from stellar atmosphere models for a given set of stellar parameters and instrumental response functions. In this thesis,

PyLDTk was used to obtain physically motivated priors for the limb-darkening coefficients adopted in the PyORBIT transit models.

For each target, the stellar effective temperature, surface gravity, and metallicity were adopted as inputs to the calculation. The corresponding instrumental response functions were provided for the *TESS* observations for all targets, the ground-based photometric observations of TOI-6105 and *Gaia*-7, and, in the case of TOI-1019 b, for each of the IMACS spectral channels. For the latter, the response functions were constructed for the wavelength intervals used to generate the chromatic light curves. The codes that I used to calculate the limb-darkening coefficients and to construct the corresponding response functions are provided in Appendices A2.

The resulting limb-darkening coefficients were incorporated as priors in the PyORBIT transit analysis, providing wavelength-dependent constraints for the IMACS chromatic light curves and appropriate constraints for the broadband *TESS* and ground-based photometric datasets.

3.4.3 The TauREx 3 software

TauREx 3 ($\mathcal{T}$ -REx 3; Al-Refaie et al., 2021, 2022) is a Bayesian atmospheric retrieval framework designed to interpret exoplanetary transmission and emission spectra. It allows the atmospheric properties of an exoplanet to be inferred by comparing observed spectra with forward models that describe the wavelength-dependent planetary radius or emergent flux. The framework can account for molecular and atomic absorption, scattering processes, collision-induced absorption, clouds, and different atmospheric composition and temperature structures.

In this thesis, $\mathcal{T}$ -REx 3 was used to investigate the atmospheric properties of TOI-1019 b using the transmission spectrum obtained from the IMACS spectrophotometric analysis. The retrieval was used to explore whether the observed wavelength-dependent variations could be explained by different atmospheric compositions and opacity sources. The specific atmospheric configurations adopted for TOI-1019 b, together with the corresponding retrieval results and their interpretation, are presented in Chapter 4.

3.4.3.1 Forward model

The forward model in $\mathcal{T}$ -REx 3 calculates the expected transmission or emission spectrum for a specified set of planetary and atmospheric parameters. For transmission spectroscopy, the model determines the wavelength-dependent atmospheric opacity and the corresponding effective planetary radius as a function of wavelength. The opacity can include contributions from molecular and atomic absorption, Rayleigh scattering, and collision-induced absorption, while additional atmospheric processes such as clouds and hazes can also be incorporated depending on the adopted model.

The atmospheric structure is described through a set of pressure layers and an associated temperature and composition profile. Molecular abundances can be specified through different parameterizations, allowing the retrieval to be performed under assumptions ranging from simplified atmospheres to models with multiple free molecular abundances. The resulting synthetic spectrum is then compared with the observed transmission spectrum within the Bayesian retrieval framework.

3.4.3.2 Sampling and model comparison

The posterior distributions were sampled using nested sampling as implemented in **MultiNest** (Feroz et al., 2009). This approach allows the posterior parameter distributions and the Bayesian evidence, $\ln Z$, to be estimated simultaneously. The Bayesian evidence was used to compare the different atmospheric model families and to assess whether the additional complexity introduced by molecular absorbers or clouds was supported by the data.

The resulting posterior distributions, Bayesian evidence values, and model comparisons were used to evaluate the range of atmospheric scenarios compatible with the observed transmission spectrum.

3.4.3.3 Application to TOI-1019 b

For TOI-1019 b, the transmission spectrum obtained from the IMACS spectrophotometric analysis and PyORBIT modeling (Section 3.4.2) was used as the input spectrum for the atmospheric retrieval. The analysis considered an isothermal atmospheric temperature–pressure profile and an H_2/He -dominated

background atmosphere. The atmosphere was discretized into pressure layers, and the forward model included the relevant molecular and atomic opacity sources, Rayleigh scattering, and collision-induced absorption.

Four retrieval model families were considered to evaluate the atmospheric scenarios required to reproduce the observed transmission spectrum: a flat model, a free-minimal model, a free model without clouds, and a free model including a grey cloud deck. The molecular species and additional atmospheric parameters considered in each model were selected according to the corresponding retrieval configuration. The planetary reference radius and atmospheric temperature were also treated as free parameters.

To explore the dependence of the retrieved atmospheric properties on the assumed planetary mass, the retrieval analysis was repeated for six different mass scenarios. These cases were treated as alternative assumptions for exploring the atmospheric solutions rather than as independent measurements of the planetary mass. The specific model configurations, parameter ranges, mass scenarios, and retrieval results are presented and discussed in Chapter 4, Section 4.6.

Chapter 4

IMACS spectrophotometric confirmation and atmospheric characterization of the hot Jupiter TOI-1019 b

4.1 Abstract

4.1.1 Abstract

This chapter presents the statistical validation and characterization of TOI-1019 b, a hot Jupiter orbiting a young main-sequence star, using *TESS* photometry, CHIRON spectroscopy, and spectrophotometric observations obtained with IMACS. The combined analysis was used to constrain the planetary properties and to obtain an optical transmission spectrum from 13 chromatic light curves. The resulting analysis yielded an orbital period of $P_{\text{orb}} \approx 5.2341$ days, a planetary radius of $R_p = 25.38 \pm 0.24 R_{\oplus}$, and an equilibrium temperature of $T_{\text{eq}} \approx 1589$ K. The atmospheric retrieval was performed under six different assumed planetary-mass scenarios to explore the sensitivity of the retrieved atmospheric properties to the planetary gravity. The resulting transmission spectrum does not provide robust evidence for the detection of specific atmospheric species, and the available data do not justify the adoption of more complex atmospheric models. These results provide a basis for future high-resolution spectroscopic observations aimed

at detecting individual spectral features and further constraining the atmospheric composition of TOI-1019 b.

4.2 Target selection and basic information

The target selection was carried out within our group by searching among the available *TESS* Objects of Interest (TOIs) for giant-planet candidates around bright main-sequence stars suitable for ground-based atmospheric characterization. The selection considered several observational and scientific criteria. The candidates were required to have a *TESS* magnitude of $T_{\text{mag}} < 12$, transits observable from Las Campanas Observatory during the 2022B semester, and favorable prospects for atmospheric characterization with JWST. The latter criterion was quantified using the predicted Transmission Spectroscopy Metric (TSM), with a threshold of $\text{TSM} \geq 90$ adopted for giant planets as a benchmark for prioritizing targets for atmospheric characterization (Kempton et al., 2018). The combination of these criteria was intended to identify targets for which optical ground-based transmission spectroscopy could provide complementary information to future infrared observations.

Among the candidates satisfying these criteria, the hot Jupiter candidate TOI-1019 b was selected for follow-up observations with Magellan/IMACS. The planet is hosted by a bright main-sequence star with $V = 10.891$, located at a previously reported distance of 399.54 pc and with a previously reported stellar mass of $M_{\star} = 1.79 M_{\odot}$. These values correspond to the stellar characterization available at the time of target selection. The stellar properties were subsequently re-evaluated as part of this work using the spectroscopic and photometric information described in Section 4.4, yielding $M_{\star} = 1.43^{+0.04}_{-0.05} M_{\odot}$ and a distance of $388.9^{+1.6}_{-1.4}$ pc (Table 4.4.1). The ground-based optical transmission spectrum obtained with IMACS was intended to complement future JWST infrared observations, providing additional wavelength coverage for the characterization of the planetary atmosphere.

4.2.1 Statistical validation

Because of the relatively large pixel scale of *TESS* ($\sim 21 \text{ pixel}^{-1}$), multiple stars can fall within a single photometric aperture. In some cases, unresolved or blended sources may therefore produce transit-like signals that mimic planetary transits,

leading to false-positive scenarios. For this reason, a probabilistic validation analysis was performed for TOI-1019 before the follow-up observations.

As a first validation step, the *Gaia* DR3 photometric catalog was inspected for sources located within the region corresponding to the *TESS* point-spread function around the host star. The purpose of this analysis was to identify nearby sources that could potentially act as blended eclipsing binaries and reproduce the observed transit signal. No *Gaia* source was identified that could plausibly account for the observed transit through such a blended configuration.

The false-positive probability (FPP) was subsequently evaluated using the *VESPA* software (Morton, 2012), following the procedure adopted by Mantovan et al. (2022). The analysis yielded an extremely low FPP, below 1%, providing statistical validation of the planetary interpretation of the transit signal. As an additional check of the planetary interpretation, a centroid-motion test (Montalto et al., 2020) was also performed. Together, these tests provided independent evidence against the main false-positive scenarios considered for the *TESS* transit signal and supported the subsequent spectrophotometric follow-up of TOI-1019.

An independent validation of TOI-1019 b was subsequently presented by Neupane and Bhandari (2025), who performed a comprehensive analysis of the system using transit observations. This independent study provides additional support for the planetary interpretation of the transit signal.

Figure 4.2.1 illustrates the location of the initially considered targets in the period–radius parameter space relative to confirmed giant planets with transmission-spectroscopy observations.

Following its identification in *TESS* photometry, TOI-1019 b was characterized as a transiting hot Jupiter candidate with an orbital period of approximately 5.234 days and a transit duration of approximately 3.71 hours. The system was observed by *TESS* in Sectors 34–36 between January and April 2021, Sectors 61–63 between January and April 2023, and Sectors 88–90 between January and April 2025. These observations provided the broadband transit photometry used in the subsequent analysis.

From the planetary properties available at the time of target selection, the theoretical TSM of TOI-1019 b was estimated to be approximately 298. This value was provided by the *TESS* Atmospheric Characterization Working Group

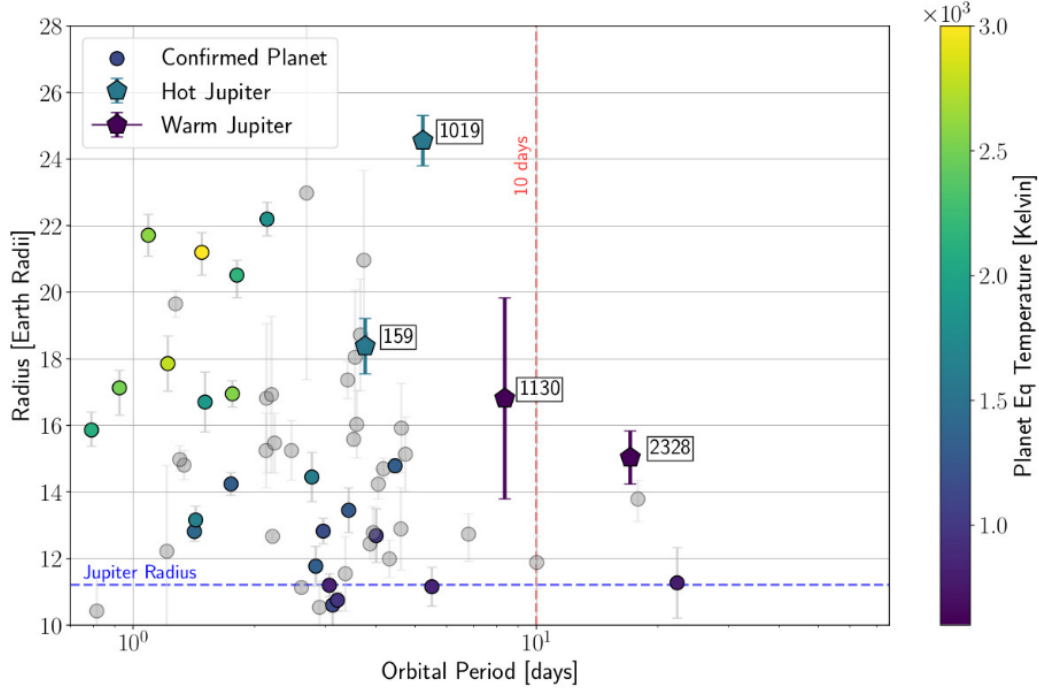


Figure 4.2.1: Orbital period vs. planetary radius of confirmed Jupiter-size exoplanets with transmission spectroscopy observations (data from NASA Exoplanet Archive). The pentagons represent the targets initially proposed for IMACS observation, while circles show confirmed planets. The planetary equilibrium temperature is color-coded. Grey circles represent planets for which no estimate of the equilibrium temperature is available.

and does not require an independently measured planetary mass. It exceeds the $TSM = 90$ threshold adopted by [Kempton et al. \(2018\)](#) for giant planets, supporting the suitability of TOI-1019 b for atmospheric characterization. The TSM and its dependence on the planetary properties are discussed further in the subsequent analysis.

4.3 Observations and data reduction

This section presents the observational data of TOI-1019 used in this work, detailing the sources from which the data were obtained and, where applicable, how they were reduced.

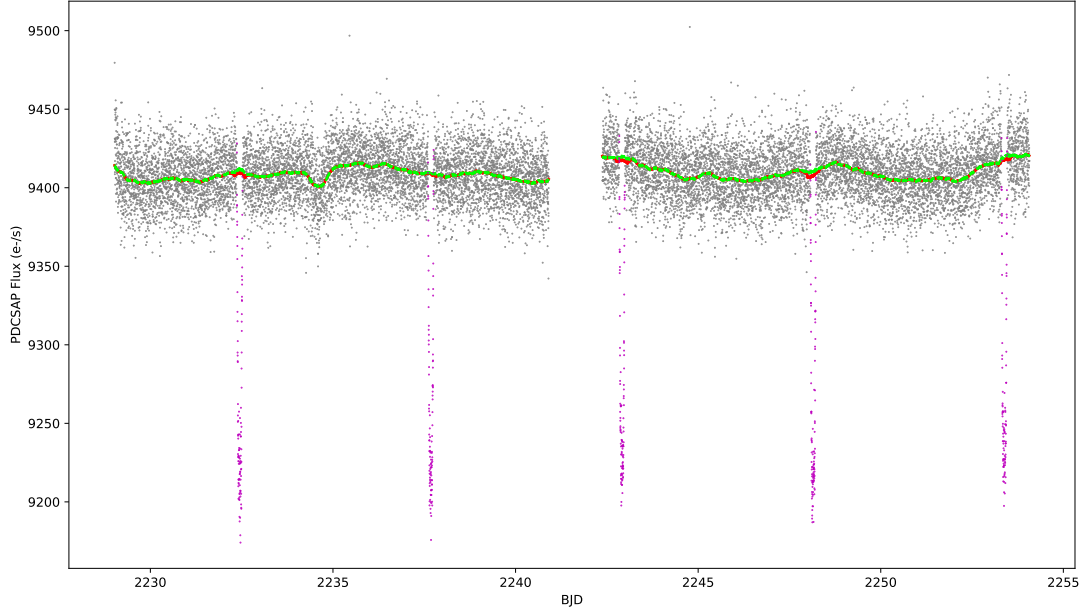


Figure 4.3.1: TESS PDCSAP normalized light curve of TOI-1019 observed in Sector 34. The grey dots represent the observed dataset at 120 s cadence. Vertical lines mark the central transit times of TOI-1019 b, with the mask used for the flattening being highlighted in purple. The line dashed line is the *wotan* biweight detrending model used to flatten the light curve.

4.3.1 *TESS* photometry

As described in Section 4.2, TOI-1019 b was identified as a candidate exoplanet by *TESS*. All observations were obtained at a 120 s cadence and processed by the *TESS* Science Processing Operations Center (SPOC, Jenkins et al., 2016) pipeline. The photometric data from all observed sectors were downloaded from the Mikulski Archive for Space Telescopes¹ (MAST). The archive provides Pre-search Data Conditioning Simple Aperture Photometry (PDCSAP; Smith et al. 2012; Stumpe et al. 2012, 2014) light curves, which are corrected for stellar dilution.

I normalized and flattened the light curves using the Tukey’s biweight detrending algorithm implemented in *wotan* (Hippke et al., 2019) (Appendix A1 shows the code used for this procedure). The transits were masked using windows three times the predicted transit duration. This procedure was used to remove long-term trends and facilitate the measurement of the transit depth of TOI-1019 b. An example of the resulting light curve for Sector 34 is shown in Figure 4.3.1.

¹<https://mast.stsci.edu/>

4.3.2 Magellan/IMACS spectrophotometry

As noted previously, the atmosphere of TOI-1019 b had not been characterized prior to this study. Therefore, constraining its atmospheric scale height H was considered relevant for investigating its atmospheric properties and structure. The primary goal was to constrain the presence of Rayleigh scattering – potentially associated with a hazy or low- μ atmosphere – by measuring the spectral slope of the continuum, and to search for optical absorbers within the IMACS (Dressler et al., 2011) wavelength range, such as Na and metal oxides and hydrides. These observations were also intended to provide an additional assessment of the metal-enrichment trends observed among giant exoplanets (Thorngren et al., 2016).

The observations covering the complete transit of TOI-1019 b were obtained during the night of 9 January 2023 (Programme CN2022B-25, PI: Villanova) with IMACS at Las Campanas Observatory in Chile. The observations were conducted in Remote mode, with the observations coordinated remotely through the LCO network in communication with the Telescope Operator and site staff. The instrumental configuration and observational methodology are described in Chapter 3, Section 3.1.

A time series of IMACS spectra covering the full transit of TOI-1019 b was obtained with a constant exposure time of 60 s, starting approximately one hour before first contact and ending approximately one hour after last contact. The inclusion of off-transit observations before and after the transit provides the baseline required to characterize and remove systematic trends in the spectrophotometric time series (e.g., Nascimbeni et al., 2013). The airmass during the observations ranged from 1.125 to 1.3.

4.3.2.1 IMACS spectrophotometry data reduction

The reduction of the IMACS observations and the extraction of the wavelength-calibrated one-dimensional spectra were performed following the procedure described in Section 3.4.1. This procedure was applied to the spectra of TOI-1019 b and the four reference stars observed simultaneously during the transit. The resulting spectra were subsequently aligned onto a common wavelength scale using the interpolation procedure described in Section 3.4.1. Examples of the spectra before and after this correction are provided in Appendix A5.1. The final

wavelength-aligned spectra were then used for the construction of the chromatic light curves described in Section 4.5.1.

4.3.3 CHIRON spectroscopic data

In order to obtain stellar parameters for the host star, three high-resolution spectra from the CHIRON spectrograph database were downloaded and combined. These observations were collected with the CHIRON spectrograph on the 1.5m SMARTS telescope at Cerro Tololo Inter-American Observatory, Chile (Tokovinin et al., 2013). CHIRON is a fiber-fed echelle spectrograph, and according to the information provided by the data author, the observations were obtained in slicer mode, with a spectral resolving power of $\lambda/\Delta\lambda \approx 80,000$ over the wavelength range of 4100–8200 Å. Spectral extractions were performed by the official CHIRON pipeline (Paredes et al., 2021).

4.4 Stellar Parameters

4.4.1 Atmospheric parameters and projected rotational velocity

From the spectroscopic data from CHIRON described in Section 4.3.3, the atmospheric parameters and projected rotational velocity of the host star were determined. The host star is a rapid rotator, resulting in broad and blended spectral lines. Consequently, Fe I and Fe II lines could not be reliably used to determine the atmospheric parameters. Instead, the H_α and H_β lines were analyzed, which, for an early-F-type star, are good temperature indicators and are largely independent of surface gravity. Atmospheric models were calculated using the ATLAS9 code (Kurucz, 1970), and synthetic spectra around the H_α and H_β lines were generated using version 2.77 of the SPECTRUM software.² The three high-resolution spectra were combined to improve the S/N, and the spectral orders were normalized while accounting for the shape of the spectrograph blaze function. This is particularly important when analyzing the H lines, as their broad profiles can mask the actual shape of the continuum if the blaze function is not properly taken into account.

²<https://www.appstate.edu/~grayro/spectrum/spectrum.html>

During the analysis, a $\log(g) = 4.30$, typical of an early-F-type main-sequence star, was adopted, while the metallicity and projected rotational velocity were obtained by fitting visible metal lines in the blue part of the spectrum. Synthetic spectra were also calculated using version 2.77 of the **SPECTRUM** software. An initial estimate of the radial velocity was obtained from the positions of the cores of the H lines. This value was subsequently refined by shifting the synthetic spectra in velocity and determining, for each order of the observed spectrum, the velocity that minimized the χ^2 . The resulting velocities were then corrected for the heliocentric effect, yielding a mean heliocentric radial velocity of $12.0 \pm 1.5 \text{ km s}^{-1}$. The resulting stellar parameters are reported in Table 4.4.1.

4.4.2 Infrared flux method and isochrones

To determine the stellar radius and mass of TOI-1019 from its atmospheric parameters (T_{eff} and $\log g$), one of our collaborators applied a modified version of a code combining the infrared flux method (IRFM, Blackwell and Shallis, 1977; Stassun et al., 2017) and isochrone fitting (MCMCI code, Bonfanti and Gillon, 2020). First, the stellar angular diameter and T_{eff} were computed using the apparent bolometric flux and the corresponding relations. In particular, a spectral energy distribution (SED) based on stellar atmospheric models (taken from the ATLAS catalogues, Castelli and Kurucz, 2003), and adjusted for extinction estimates (Bovy et al., 2016; Green et al., 2019), was constructed using the atmospheric parameters as priors. The stellar bolometric flux was then derived by comparing synthetic photometry computed from the SED with observational data from the *Gaia* G , G_{BP} , and G_{RP} , 2MASS J , H , and K , and WISE W1 and W2 bandpasses. The stellar radius $R_{\star}$ was subsequently estimated from the stellar angular diameter using the offset-corrected *Gaia* Early Data Release 3 parallax (Lindgren et al., 2021). Finally, using $R_{\star}$ as an input, the stellar mass $M_{\star}$ and age $t_{\star}$ were determined through the isochrone placement algorithm (Bonfanti et al., 2015), which interpolates the stellar parameters within precomputed grids of PARSEC v1.2S (Marigo et al., 2017) isochrones and evolutionary tracks. The resulting stellar parameters are reported in Table 4.4.1.

Table 4.4.1: Stellar properties of TOI-1019.

Parameter	TOI-1019	Reference
α (ICRS)	08:00:35.539	<i>Gaia</i> DR3
δ (ICRS)	−54:52:42.826	<i>Gaia</i> DR3
μ_α (mas yr ^{−1})	−11.627 ± 0.014	<i>Gaia</i> DR3
μ_δ (mas yr ^{−1})	2.572 ± 0.014	<i>Gaia</i> DR3
RV (km s ^{−1})	7.89 ± 1.92	<i>Gaia</i> DR3
π (mas)	2.559 ± 0.012	<i>Gaia</i> DR3
V (mag)	10.891 ± 0.008	Henden et al. (2016)
G (mag)	10.885 ± 0.006	<i>Gaia</i> DR3
$G_{BP} - G_{RP}$ (mag)	0.489 ± 0.009	<i>Gaia</i> DR3
J (mag)	10.178 ± 0.024	2MASS
H (mag)	10.083 ± 0.023	2MASS
K (mag)	10.017 ± 0.021	2MASS
T_{eff} (K)	6900 ± 100	Spec; Sect. 4.4.1
T_{eff} (K)	6900 ⁺⁹⁸ _{−96}	SED; Sect. 4.4.2
[Fe/H] (dex)	+0.00 ± 0.05	Spec; Sect. 4.4.1
[Fe/H] (dex)	−0.01 ± 0.10	SED; Sect. 4.4.2
log g	4.17 ± 0.02	SED; Sect. 4.4.2
RV (km s ^{−1})	12.0 ± 1.5	Spec; Sect. 4.4.1
vsini (km s ^{−1})	75 ± 5	Spec; Sect. 4.4.1
Luminosity (L _⊙)	5.36 ± 0.32	Sect. 4.4.2
Radius (R _⊙)	1.62 ± 0.02	Sect. 4.4.2
Mass (M _⊙)	1.43 ^{+0.04} _{−0.05}	Sect. 4.4.2
Density ($\rho_\odot$)	0.33 ± 0.01	Sect. 4.4.2
Age (Gyr)	1.3 ^{+0.3} _{−0.2}	Sect. 4.4.2
Distance (pc)	388.9 ^{+1.6} _{−1.4}	Bailer-Jones et al. (2021)

4.5 Data Analysis and Sample Study

4.5.1 Chromatic light curve creation

From the observations described in Section 4.3.2, a time series of IMACS spectra covering the full transit of TOI-1019 b was obtained with a constant exposure time of 60 s, starting approximately one hour before first contact and ending approximately one hour after last contact. The reduction and wavelength alignment of these spectra were performed following the procedure described in Section 4.3.2.1. The median spectra obtained for TOI-1019 and the four reference stars are shown in Figure 4.5.1.

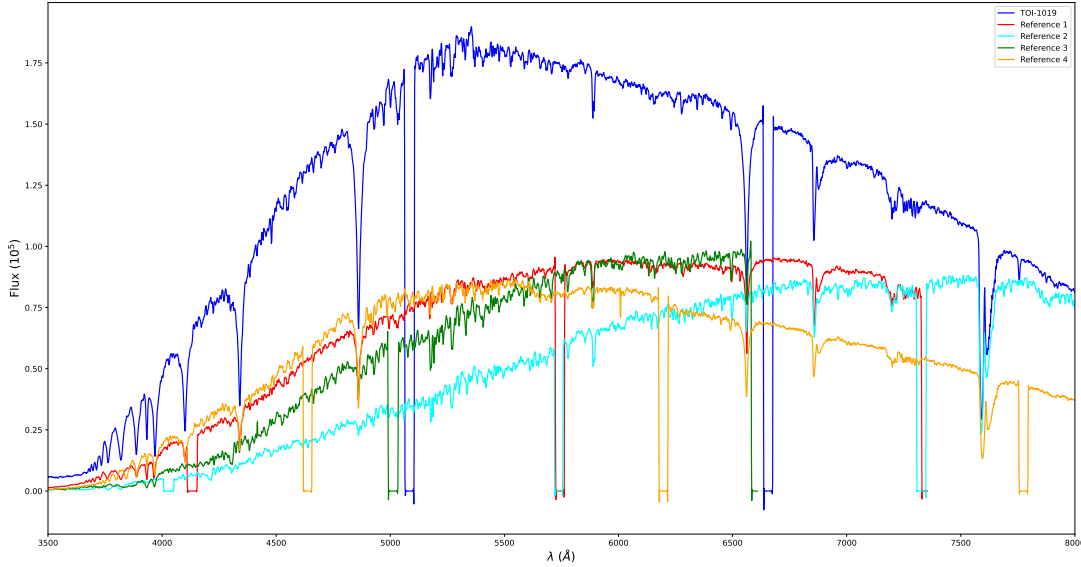


Figure 4.5.1: Spectra of all five stars that were observed. The spectrum of TOI-1019 is shown in blue, while the spectrum of the different reference stars, from #1 to #4 are shown in red, cyan, green, and orange, respectively. Each spectra displays in some sections a rectangular shape, corresponding to the CCD gaps from IMACS.

From Figure 4.5.1, it can be seen that the spectrum of reference star #3 (green) does not extend beyond approximately 6600 Å. This incomplete wavelength coverage would prevent its use as a reference star over the full wavelength range considered in the analysis and could introduce systematic differences when constructing the differential light curves. Therefore, reference star #3 was excluded from the subsequent analysis. Reference star #4 (orange) was also excluded because its light curve showed an anomalous behavior in the bluest

spectral channel (3700–4000 Å), displaying a continuous slope rather than the flux decrease and subsequent increase observed in the other spectral channels. To avoid introducing additional systematic effects into the spectrophotometric analysis, reference star #4 was therefore also discarded.

With reference stars #3 and #4 excluded, the spectrum of TOI-1019 and the two remaining reference stars were divided into 14 wavelength bins, or spectral channels, with widths ranging from 100 to 300 Å. The wavelength intervals were selected to avoid the CCD gaps and the main telluric absorption region associated with the O₂ band around 685.7 nm. The resulting wavelength bins are shown in Figure A5.3 in the Appendix.

For each spectral channel, chromatic light curves were constructed by summing the flux counts within the corresponding wavelength interval of the TOI-1019 spectrum and dividing this value by the summed counts from the reference star(s) in the same wavelength interval. This procedure was repeated for each spectrum in the time series. The time associated with each spectrum was obtained from the JD value recorded in the corresponding FITS header, corrected to the center of the exposure, and converted to the BJD_{TDB} time standard following the prescription of Eastman et al. (2010).

I defined the wavelength binning scheme considering the expected spectrophotometric precision, the wavelength coverage available in the observations, regions of strong telluric absorption, and the objective of probing potential atmospheric features such as a scattering slope and absorption from sodium and potassium. The wavelength intervals used to construct the transmission spectrum are shown as shaded regions in Figure A5.3, and their wavelength ranges are listed in the first column of Table 4.5.2. The detrending procedure applied to the resulting chromatic light curves is described in Section 4.5.3.

The initial chromatic light curves obtained using reference stars #1 and #2 are shown in Figure 4.5.2. Reference star #1 provides spectral coverage over the first 13 spectral channels but does not cover channel 14 (7365–7565 Å). To ensure a homogeneous differential-photometry analysis using the same wavelength coverage for both reference stars, the final analysis was therefore restricted to the 13 spectral channels covered by both reference stars.

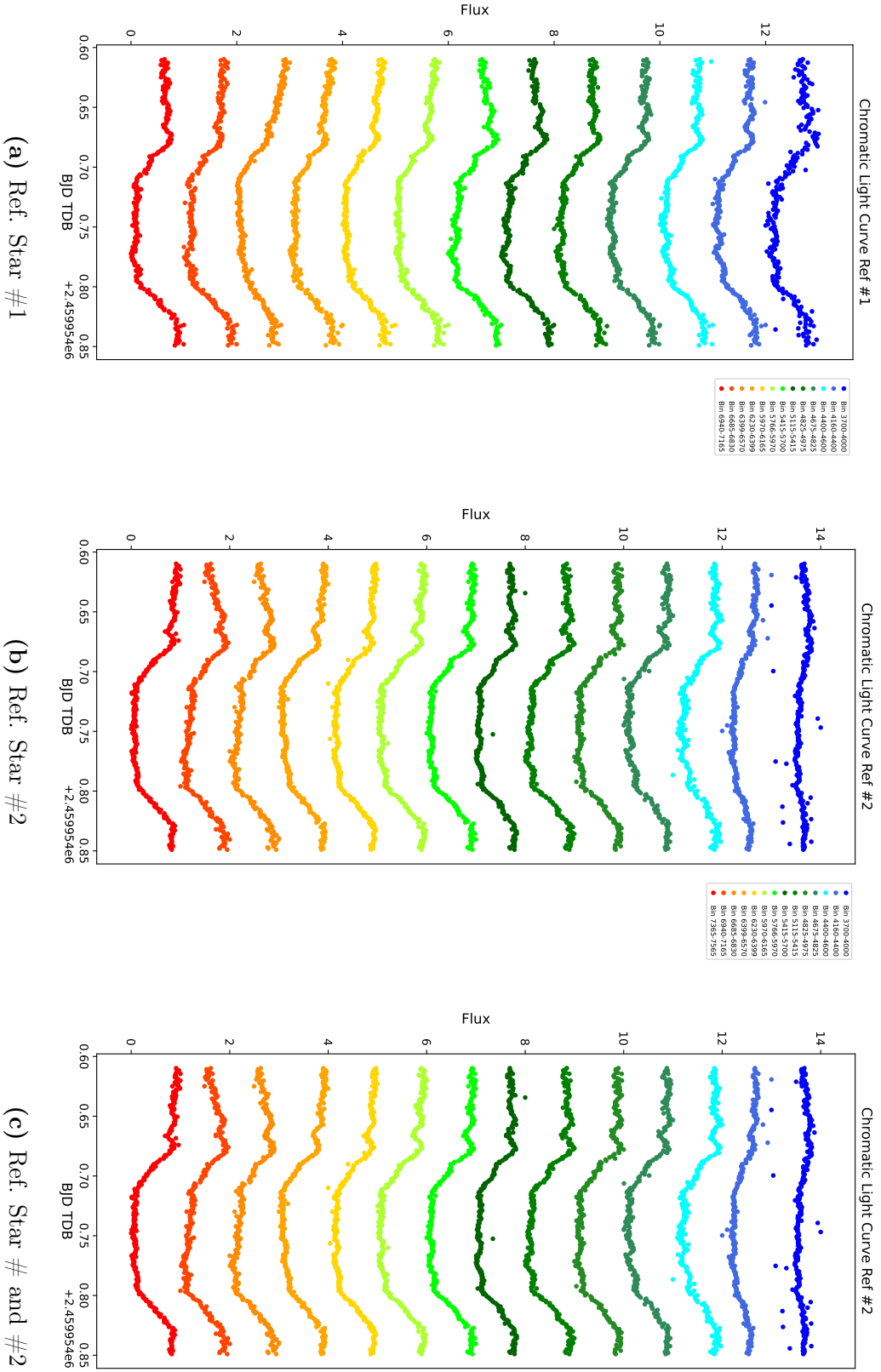


Figure 4.5.2: Chromatic light curves of the two reference stars that were considered for the transit analysis, Ref. #1 (left) and Ref. #2 (middle), as well as their combined light curve (right). The x-axis shows the time in BJD TDB and the y-axis the normalized flux. Each corresponding spectral channel is displayed with different color, with the bluest wavelength (3700-4000 Å) being at the top, and the redder at the bottom (6940-7165 Å for light curves 4.5.2a and 4.5.2c, and 7365-7565 Å for light curve 4.5.2b).

4.5.2 *TESS* modeling

As described in Chapter 2.4, *TESS* provides an extensive archive of photometric observations that can be used to characterize and confirm the planetary nature of transiting candidates. To estimate the planetary properties of TOI-1019 b, I performed a Bayesian transit analysis using the PyORBIT package (Malavolta, 2016), as described in Chapter 3.4.2.

The initial analysis was performed using the six *TESS* sectors available at the time. Following the availability of additional observations from Sectors 88–90, the analysis was updated using all nine sectors in which TOI-1019 was observed, as described in Sections 4.2 and 4.3.1. For the updated analysis, the stellar parameters determined in this thesis were adopted, together with the planetary constraints obtained from the previous analysis.

For the final analysis, the transit signal in each sector was simultaneously modeled using the BATMAN code (Kreidberg, 2015). The fitted parameters included the reference transit time (T_0), the impact parameter (b), the orbital period (P_{orb}), the stellar density (ρ_*), the quadratic limb-darkening (LD) coefficients, u_1 and u_2 , adopting the LD parameterization introduced by Kipping (2013), and a jitter term added in quadrature to the photometric uncertainties to account for effects not captured by the model, such as short-term stellar variability, or for possible underestimation of the reported uncertainties. The orbital period was fitted in linear space, and a circular orbit was assumed. Gaussian priors were imposed on the LD coefficients and stellar density, while uniform priors were adopted for P_{orb} and T_0 . The LD coefficients were estimated using PyLDTk³ (Husser et al., 2013; Parviainen and Aigrain, 2015) for the *TESS* passband, following the procedure described in Chapter 3.4.2. An additional uncertainty of 0.1 was added in quadrature to the LD coefficient uncertainties to account for the known underestimation of model uncertainties. The priors and posterior values from the final *TESS* photometric analysis is presented in Table 4.5.1.

For the modeling, I first performed a global optimization of the parameters using a differential evolution algorithm (Storn and Price, 1997, PyDE⁴), followed by a Bayesian analysis using the affine-invariant ensemble sampler (Goodman and

³<https://github.com/hpparvi/ldtk>

⁴<https://github.com/hpparvi/PyDE>

Table 4.5.1: Priors and outcomes of *TESS* photometric modeling.

Planetary parameters		TOI-1019 b	
Parameter	Unit	Prior	Value
Orbital period (P_{orb})	days	$\mathcal{U}(5.22, 5.24)$	5.2340994 ± 0.0000006
Central time of transit (T_0)	BTJD	$\mathcal{U}(2231, 2233)$	2232.44689 ± 0.00011
Scaled semi-major axis ($\frac{a}{R_\star}$)		...	$9.602^{+0.048}_{-0.046}$
Orbital semi-major axis (a)	AU	...	0.0725 ± 0.0008
Orbital inclination (i)	deg	...	85.68 ± 0.05
Orbital eccentricity (e)		0.0	0.0
Impact parameter (b)		$\mathcal{U}(0, 1)$	0.723 ± 0.005
Planet/star radius ratio ($\frac{R_p}{R_\star}$)		$\mathcal{U}(0, 0.5)$	0.1432 ± 0.0004
Argument of pericenter (ω)	deg	...	90
Mean longitude (L)	deg	...	59.26 ± 0.01
Transit duration (T_{14})	days	...	0.1543 ± 0.0003
Planetary radius (R_p)	$R_\oplus$	...	$25.38^{+0.27}_{-0.26}$
Stellar parameters		TOI-1019	
Parameter	Unit	Prior	Value
Density ($\rho_\star$)	$\rho_\odot$	$\mathcal{N}(0.335, 0.016)$	0.349 ± 0.006

Weare, 2010) for Markov chain Monte Carlo, as implemented in *emcee* (Foreman-Mackey et al., 2013). I used $4n_{\text{dim}}$ walkers, where n_{dim} represents the model dimensionality, for 100000 generations with PyDE, followed by 100000 steps with *emcee*. A thinning factor of 200 was applied to mitigate the effect of chain autocorrelation. The first 25000 steps were discarded as burn-in after checking the convergence of the chains using the Gelman–Rubin statistic (Gelman and Rubin, 1992). The resulting posterior distributions were used to obtain the planetary parameters reported in Table 4.5.1. These results were subsequently adopted as priors for the spectrophotometric analysis of the IMACS data described in Section 4.5.3.

4.5.3 Spectrophotometric analysis

Following the photometric modeling of TOI-1019 b using the *TESS* data, I performed the transit analysis of the 13 chromatic light curves constructed using reference stars #1 and #2 (Figure 4.5.2c). The planetary parameters obtained from the final *TESS* analysis were adopted as priors for the IMACS spectrophotometric modeling, while the stellar parameters were updated using the values reported in

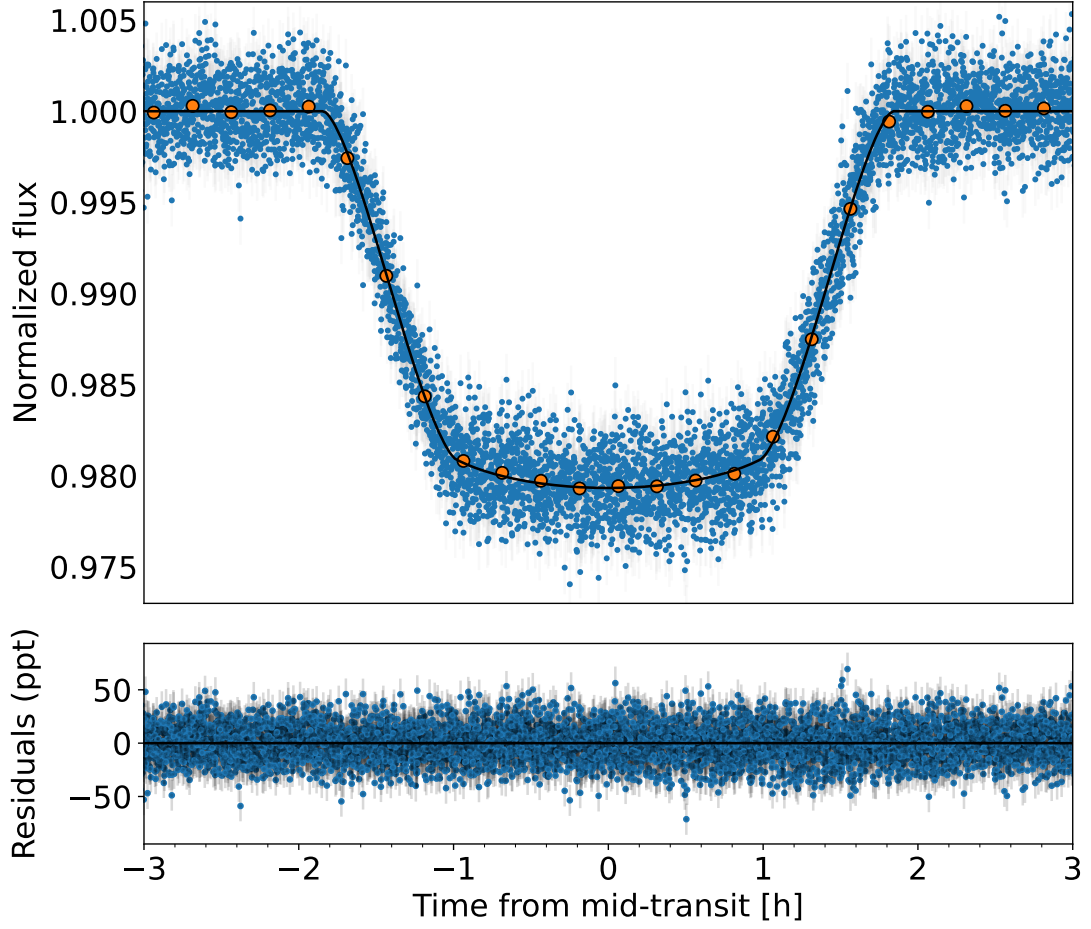


Figure 4.5.3: Photometric modeling of TOI-1019 b planetary signal. *Top panel:* *TESS* phase-folded transits of TOI-1019 b together with the transit model (black line). *Bottom panel:* Residuals of the fit.

Table 4.4.1. Limb-darkening coefficients were calculated independently for each IMACS spectral channel using PyLDTk; the corresponding procedure and code are described in Appendix A2.2.

I performed the PyORBIT analysis independently for each of the 13 spectral channels. The transit model included a Gaussian Process with a Matern 3/2 kernel to account for correlated noise in the IMACS light curves, as described in Section 3.4.2. For each channel, the posterior distribution of the planet-to-star radius ratio was obtained, from which the corresponding transit depth was derived. The resulting best-fit transit models are shown in Figures 4.5.4, 4.5.5, and 4.5.6, while the posterior estimates of $R_p/R_\star$ and the corresponding transit depths are reported in Table 4.5.2.

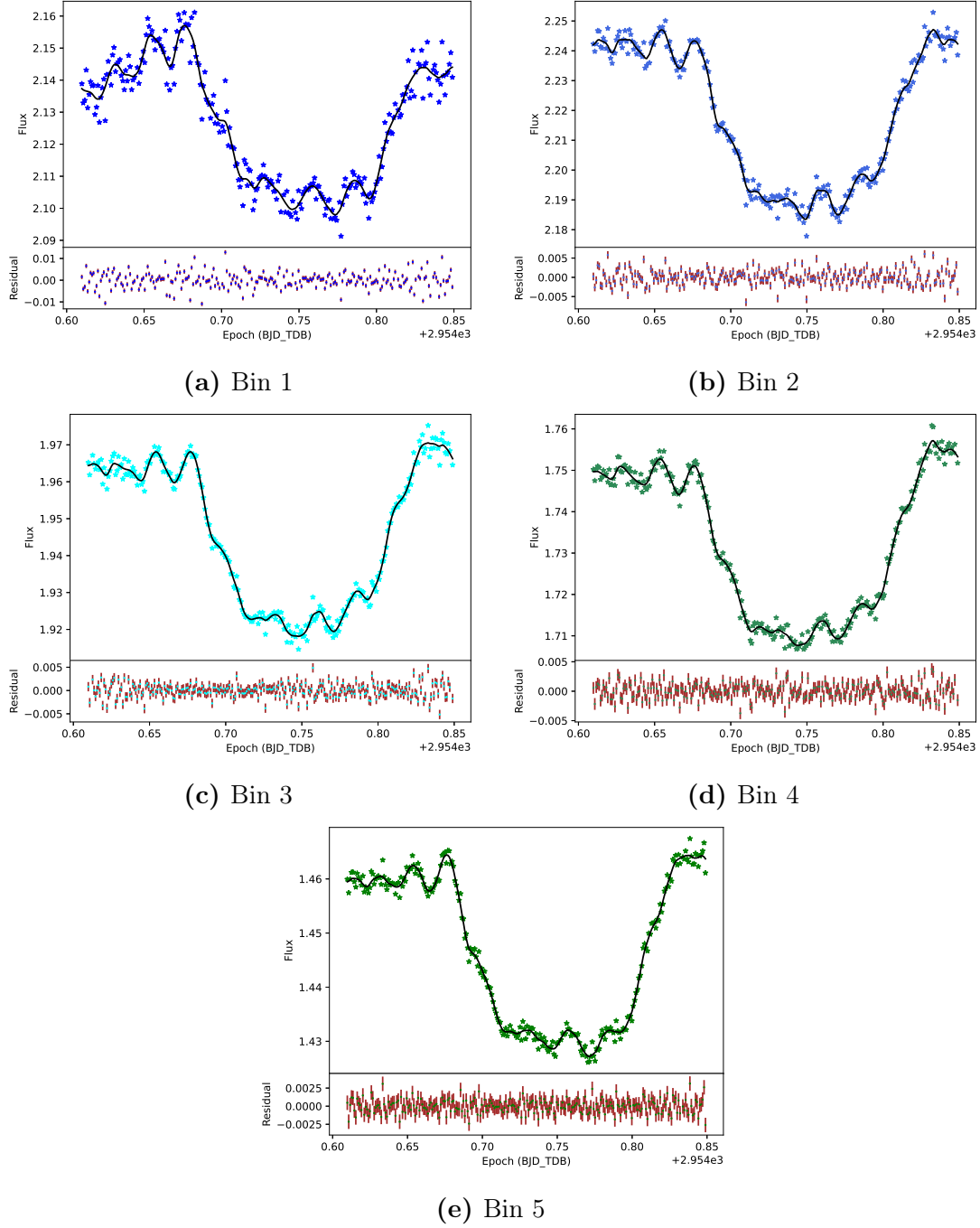


Figure 4.5.4: Transit models for the first five spectral channels (1–5) obtained from the chromatic light curves constructed using Reference #1+#2 (top), together with their residuals (bottom). The colors of the light curves correspond to the spectral-channel colors used in Figure 4.5.2, while the best-fit models are shown as black lines.

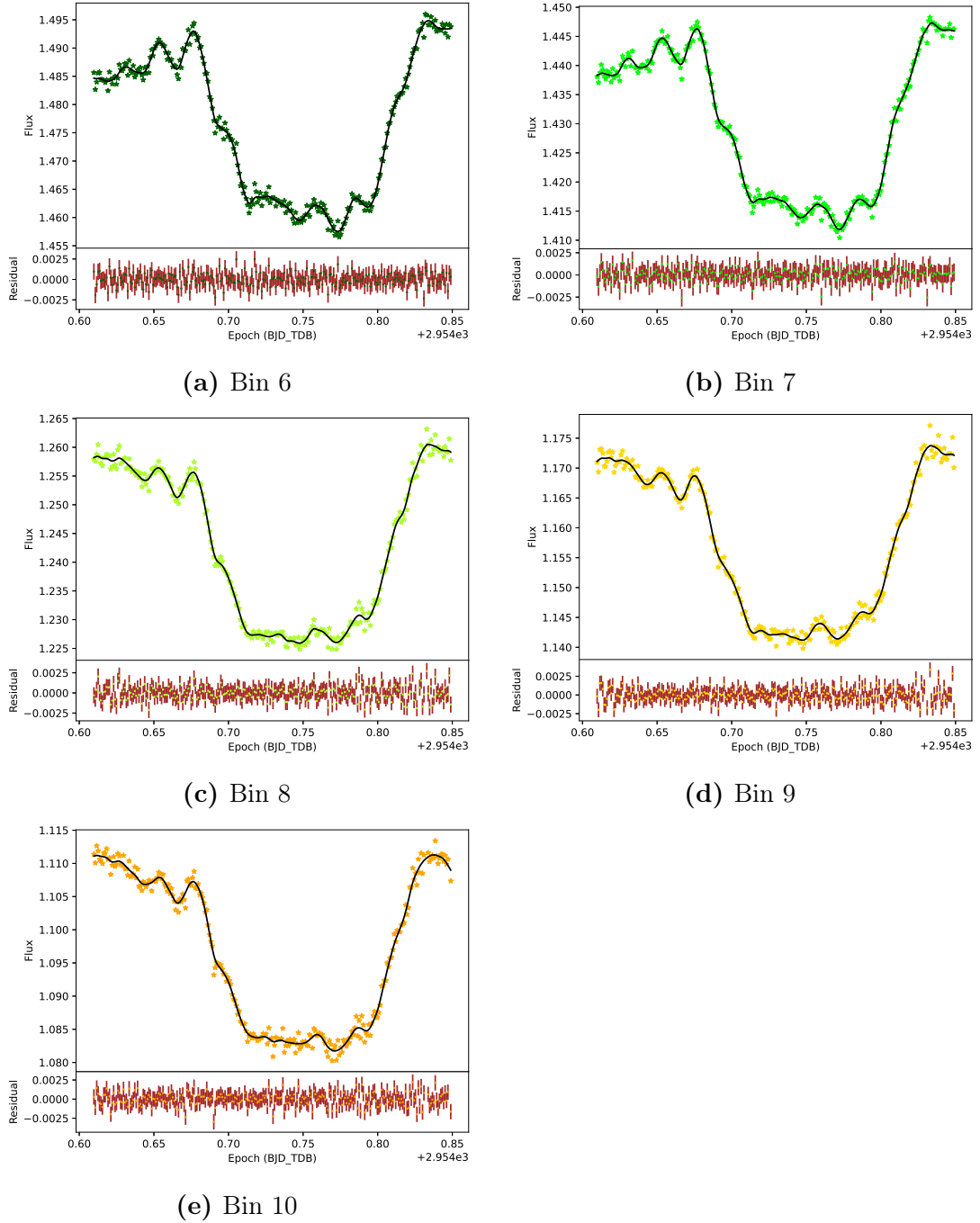
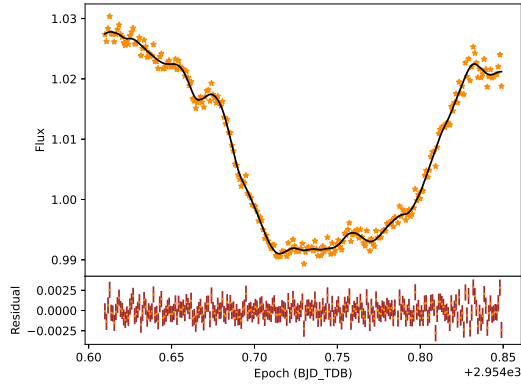
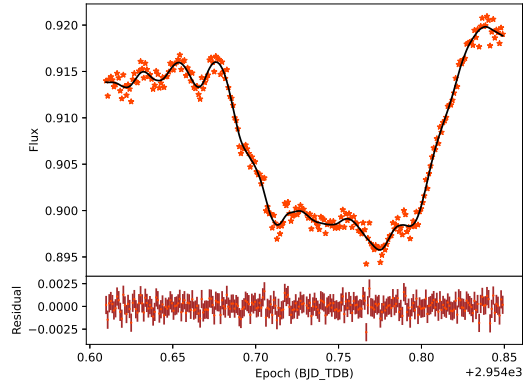


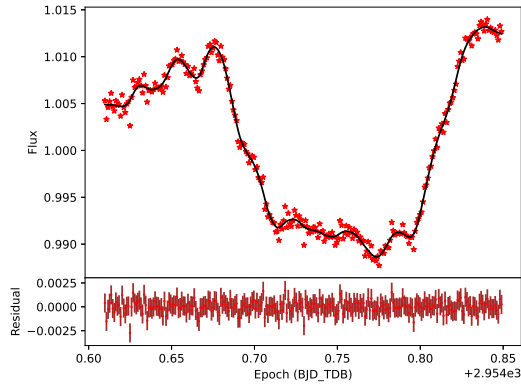
Figure 4.5.5: Transit models for spectral channels 6–10 obtained from the chromatic light curves constructed using Reference #1+#2 (top), together with their residuals (bottom). The colors of the light curves correspond to the spectral-channel colors used in Figure 4.5.2, while the best-fit models are shown as black lines.



(a) Bin 11



(b) Bin 12



(c) Bin 13

Figure 4.5.6: Transit models for the remaining spectral channels (11–13) obtained from the chromatic light curves constructed using Reference #1+#2 (top), together with their residuals (bottom). The colors of the light curves correspond to the spectral-channel colors used in Figure 4.5.2, while the best-fit models are shown as black lines.

Table 4.5.2: The planet-to-star radius ratio ($R_p/R_\star$) and corresponding transit depth $((R_p/R_\star)^2)$ for each spectroscopic wavelength channel of TOI-1019 b.

Channel	Wavelength (Å)	$R_p/R_\star$	$(R_p/R_\star)^2$
1	3700 – 4000	$0.1369^{+0.0071}_{-0.0080}$	$0.01874^{+0.0019}_{-0.0022}$
2	4160 – 4400	$0.1540^{+0.0037}_{-0.0039}$	$0.02372^{+0.0011}_{-0.0012}$
3	4400 – 4600	$0.1489^{+0.0048}_{-0.0052}$	$0.02217^{+0.0014}_{-0.0015}$
4	4675 – 4825	$0.1508^{+0.0051}_{-0.0059}$	$0.02274^{+0.0015}_{-0.0018}$
5	4825 – 4975	$0.1465^{+0.0044}_{-0.0047}$	$0.02146^{+0.0013}_{-0.0014}$
6	5115 – 5415	$0.1388^{+0.0072}_{-0.0075}$	$0.01927^{+0.0020}_{-0.0021}$
7	5415 – 5700	$0.1386^{+0.0066}_{-0.0069}$	$0.01921^{+0.0018}_{-0.0019}$
8	5766 – 5970	$0.1548^{+0.0047}_{-0.0052}$	$0.02396^{+0.0015}_{-0.0016}$
9	5970 – 6165	$0.1541^{+0.0052}_{-0.0059}$	$0.02375^{+0.0016}_{-0.0018}$
10	6230 – 6399	$0.1529^{+0.0045}_{-0.0050}$	$0.02338^{+0.0014}_{-0.0015}$
11	6399 – 6570	$0.1639^{+0.0094}_{-0.0150}$	$0.02686^{+0.0031}_{-0.0049}$
12	6685 – 6830	$0.1403^{+0.0068}_{-0.0071}$	$0.01968^{+0.0019}_{-0.0020}$
13	6940 – 7165	$0.1363^{+0.0080}_{-0.0083}$	$0.01858^{+0.0022}_{-0.0023}$

4.5.4 Transmission Spectrum

The transmission spectrum of TOI-1019 b was obtained from the wavelength-dependent transit depths measured through the analysis of the chromatic light curves. As described in Section 3.3, the chromatic light curves provide the wavelength-dependent transit measurements from which the transmission spectrum is constructed. In the analysis described in Section 4.5.3, an independent $R_p/R_\star$ parameter was fitted for each chromatic light curve. The resulting transmission spectrum, expressed as the transit depth $(R_p/R_\star)^2$ as a function of wavelength, is shown in Figure 4.5.7.

The transmission spectrum exhibits wavelength-dependent variations across the observed range. In particular, the transit depth increases from the bluest spectral channel toward wavelengths of approximately $0.45 \mu\text{m}$. However, the first spectral channel shows a lower transit depth than the adjacent channels, preventing this variation from being interpreted as a clear monotonic blueward slope. A higher transit depth is also observed around $0.65 \mu\text{m}$, corresponding to spectral channel 11, although this measurement is associated with relatively large uncertainties.

These variations may arise from a combination of atmospheric and stellar effects. In particular, atmospheric scattering can produce wavelength-dependent variations toward shorter wavelengths, while stellar heterogeneities such as unocculted spots

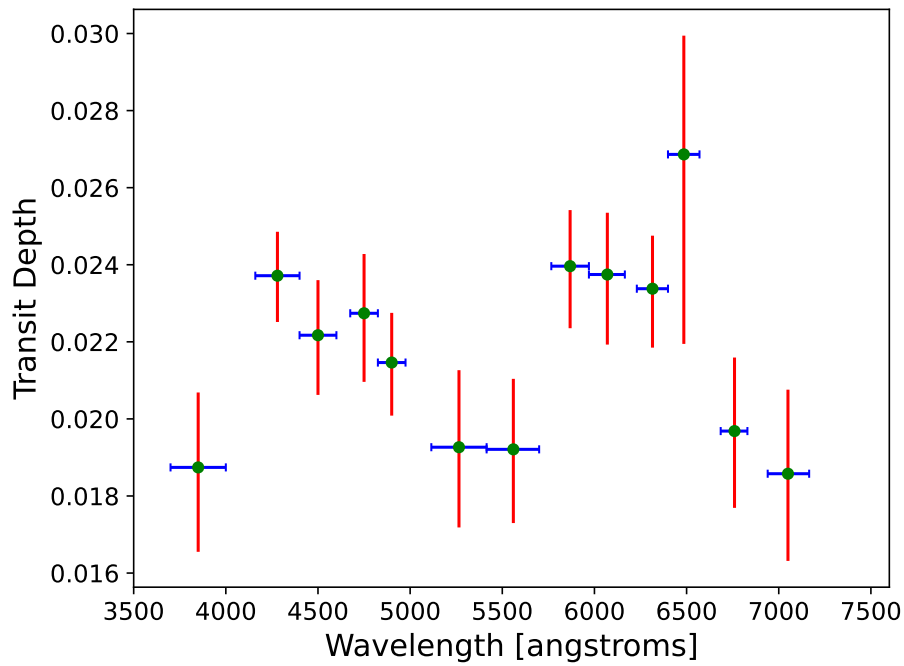


Figure 4.5.7: Transmission spectrum of TOI-1019 b derived from the IMACS spectrophotometric analysis, shown as transit depth $(R_p/R_\star)^2$ as a function of wavelength. The blue horizontal error bars indicate the wavelength range of each spectrophotometric channel, corresponding to the wavelength intervals listed in Table 4.5.2.

or faculae can also modify the observed transit depth as a function of wavelength. However, the observed spectrum alone does not provide sufficient evidence to distinguish between these possibilities. The treatment of the chromatic light curves included correlated noise through a Gaussian Process with a Matérn 3/2 kernel, reducing the likelihood that the measured variations are interpreted under a purely white-noise assumption. Nevertheless, the transmission spectrum does not exhibit a clear monotonic slope or an isolated feature with sufficient significance to support an unambiguous atmospheric interpretation.

This interpretation is consistent with the atmospheric retrieval analysis presented in Section 4.6. Across the explored planetary-mass scenarios and atmospheric model families, the retrieved spectra provide comparable descriptions of the observations, while the differences in Bayesian evidence between model configurations remain small. In particular, no individual absorbing species or cloud configuration is robustly required by the current data. Therefore, the observed wavelength-dependent variations are best regarded as tentative spectral structure rather than as a statistically significant detection of atmospheric scattering or a specific molecular or atomic feature. A more definitive characterization of the atmosphere will require higher-precision spectrophotometric observations and, in particular, an independent measurement of the planetary mass.

4.5.5 Ephemeris improvement

An important step in assessing the resulting transit ephemeris of TOI-1019 b, obtained from the analysis presented in Section 4.5, was to propagate its timing uncertainty to 1 January 2030 ($\text{BJD}_{\text{TDB}} = 2462502.5$). For this purpose, I calculated the number of orbital cycles between the reference transit time T_0 and the target date as

$$N = \frac{2462502.5 - T_0}{P}, \quad (4.5.1)$$

where N is the number of orbital cycles between the reference transit time T_0 and the target date, and P is the orbital period of the planet. The resulting value of N was rounded to the nearest integer. I then calculated the corresponding uncertainty in the predicted transit time as

$$\sigma_{T_{2030}} = \sqrt{\sigma_{T_0}^2 + (N \cdot \sigma_P)^2}, \quad (4.5.2)$$

where σ_{T_0} and σ_P are the uncertainties in the reference transit time and orbital period, respectively.

The propagated uncertainty for TOI-1019 b was estimated to be 0.55 minutes in 2030. This represents a 49% reduction relative to the uncertainty of 1.09 minutes obtained by propagating the ephemeris available from the ExoFOP database.

4.5.6 Planet Equilibrium Temperature

To compute the equilibrium temperature T_{eq} of TOI-1019 b, I assumed zero Bond albedo and full day–night heat redistribution and used the following relation:

$$T_{\text{eq}} = T_{\text{eff}} \sqrt{\frac{R_{\star}}{a}} \left(\frac{1}{4} \right)^{1/4}, \quad (4.5.3)$$

where T_{eff} is the stellar effective temperature, $R_{\star}$ is the stellar radius, and a is the orbital semi-major axis. Using the stellar and planetary parameters obtained in Sections 4.4 and 4.5, respectively, I calculated an equilibrium temperature of $T_{\text{eq}} = 1589.32 \pm 200$ K, including the propagation of the corresponding parameter uncertainties. This value is consistent with the equilibrium temperature of $T_{\text{eq}} = 1574.84$ K reported by the *TESS* project through ExoFOP.

4.5.7 Exploration of planetary mass scenarios

No independent mass measurement is currently available for TOI-1019 b. I therefore explored a range of planetary-mass scenarios to provide context for the subsequent atmospheric analysis and to evaluate the sensitivity of the transmission spectrum to the assumed planetary gravity. As a first approach, I considered empirical mass–radius relations. In particular, [Chen and Kipping \(2017\)](#), as implemented by [Louie et al. \(2018\)](#), provide a probabilistic framework for predicting planetary masses from their measured radii. However, the derived planetary radius ($R_p \approx 25, R_{\oplus}$) lies above the 95% credible interval of the forecast range for hot Jupiters, preventing a reliable mass estimate from this relation.

I therefore applied the MassSpec approach of [de Wit and Seager \(2013\)](#) to explore

the range of planetary masses that could be associated with the observed amplitude of the transmission-spectrum variations. In this approach, the amplitude of spectral features in transmission spectroscopy is related to the atmospheric scale height,

$$H = \frac{k_B T_{\text{eq}}}{\mu g}, \quad g = \frac{GM_p}{R_p^2}, \quad (4.5.4)$$

where g is the planetary surface gravity and μ is the atmospheric mean molecular weight. The characteristic amplitude of a transmission feature can be approximated as

$$\Delta\delta \approx \frac{2NHR_p}{R_\star^2}, \quad (4.5.5)$$

where N is the number of atmospheric scale heights probed and $\Delta\delta$ is the corresponding variation in transit depth. Using the transit-depth measurements listed in Table 4.5.2, I calculated a standard deviation of $\sigma_\delta = 0.0024$ across the 13 spectral channels. Assuming $\mu = 2.3$, representative of a solar-composition H_2/He atmosphere, and considering $N = 3\text{--}5$ scale heights, I used these relations to calculate the corresponding values of H , g , and M_p .

I then used the resulting values to define a set of fixed-mass scenarios for the subsequent atmospheric retrieval analysis. This procedure should not be interpreted as an independent measurement of the planetary mass, since the mass scenarios are derived from the same transmission spectrum that is subsequently modeled. In addition, the inferred spectral amplitude depends on assumptions about the atmospheric composition, temperature, mean molecular weight, and number of scale heights probed. The exercise therefore provides a sensitivity test of the atmospheric interpretation to the assumed planetary mass rather than a dynamical mass constraint.

Two sets of scenarios were considered according to the amplitude adopted in the MassSpec calculation. The conservative scenarios are based on the 1σ dispersion of the full transmission spectrum and correspond to $M_p = 0.36\text{--}0.60, M_{\text{Jup}}$ for $N = 3\text{--}5$. The optimistic scenarios are based on the larger peak-to-peak variation across the spectrum and correspond to $M_p = 0.11\text{--}0.18, M_{\text{Jup}}$. The latter range is strongly influenced by the higher transit depth measured in spectral Channel 11, whose deviation from the surrounding measurements has a significance of only $\sim 1.1\sigma$. Consequently, I consider the conservative scenarios more representative of the overall spectral dispersion, while the optimistic scenarios are retained to

explore the sensitivity of the atmospheric models to lower planetary masses.

The resulting mass scenarios and their corresponding Transmission Spectroscopic Metric values are summarized in Table 4.5.3. The atmospheric implications of these fixed-mass scenarios are investigated in Section 4.6.

4.5.8 Transmission Spectroscopic Metric determination

Using the fixed-mass scenarios explored in Section 4.5.7, I calculated the Transmission Spectroscopic Metric (TSM) for each scenario to evaluate the potential suitability of TOI-1019 b for atmospheric characterization with the *James Webb Space Telescope* (JWST). The TSM provides a relative metric for prioritizing exoplanets for atmospheric characterization by combining the planetary radius, equilibrium temperature, stellar radius, host-star brightness, and planetary mass (Kempton et al., 2018). I calculated the TSM following the definition of Kempton et al. (2018):

$$\text{TSM} = S \times \frac{R_p^3 \times T_{\text{eq}}}{M_p \times R_\star^2} \times 10^{-m_J/5}, \quad (4.5.6)$$

where $S = 1.15$ is the scale factor adopted for planets with $R_p > 4, R_\oplus$ (Kempton et al., 2018).

Using the corresponding planetary and stellar parameters, I obtained TSM values ranging from approximately 525 to 2715 across the six fixed-mass scenarios (Table 4.5.3). The lowest value, $\text{TSM} \approx 525$, corresponds to the highest planetary mass considered ($0.60, M_{\text{Jup}}$), whereas the lower-mass scenarios yield progressively larger TSM values because the metric scales inversely with planetary mass.

For comparison, the theoretical TSM reported for TOI-1019 b is approximately 298. The values calculated for the mass scenarios explored in this work are therefore higher than this theoretical estimate, indicating that TOI-1019 b could be a favorable target for atmospheric characterization if its actual mass lies within the explored range. However, because the planetary mass is not independently measured, these TSM values should be regarded as scenario-dependent rather than as a definitive property of the system. In particular, the largest TSM values correspond to the optimistic low-mass scenarios, which are also the scenarios most strongly affected by the low-significance spectral variation involving Channel 11.

I therefore interpret the TSM results as an assessment of the potential observational value of TOI-1019 b rather than as evidence for a particular planetary mass. An independent radial-velocity mass measurement would allow the TSM to be determined more robustly and would provide a more reliable assessment of the planet’s suitability for atmospheric characterization with JWST.

Table 4.5.3: Fixed planetary-mass scenarios explored using the transmission-spectrum scale-height argument of [de Wit and Seager \(2013\)](#) and the corresponding Transmission Spectroscopic Metric (TSM) values calculated following [Kempton et al. \(2018\)](#). The optimistic scenarios are based on the larger peak-to-peak spectral variation and are strongly influenced by Channel 11, whose deviation has a significance of only $\sim 1.1\sigma$. The conservative scenarios are based on the 1σ dispersion of the full transmission spectrum. The listed masses represent fixed scenarios for the atmospheric analysis and are not independent planetary-mass measurements.

Scenario	$M_p (M_{\text{Jup}})$	$M_p (M_{\oplus})$	TSM
Conservative ($N = 5$)	0.60	190	525
Conservative ($N = 4$)	0.48	152	679
Conservative ($N = 3$)	0.36	114	906
Optimistic ($N = 5$)	0.18	58	1626
Optimistic ($N = 4$)	0.15	46	2248
Optimistic ($N = 3$)	0.11	35	2715

4.6 Atmospheric retrieval

We performed a Bayesian atmospheric retrieval analysis of the IMACS transmission spectrum of TOI-1019 b using the TAUREX 3 framework ([Al-Refaie et al., 2021, 2022](#)). The forward model accounts for molecular and atomic absorption, Rayleigh scattering, and $\text{H}_2\text{--H}_2/\text{H}_2\text{--He}$ collision-induced absorption, with stellar fluxes interpolated from the PHOENIX stellar-atmosphere library ([Husser et al., 2013](#)). Posterior sampling and Bayesian-evidence estimation were performed using MultiNest nested sampling ([Feroz et al., 2009](#)). The retrievals were applied to the 13 chromatic transit-depth measurements described in Section 4.5.3, covering approximately $0.39\text{--}0.71\ \mu\text{m}$. Given the absence of an independent planetary mass constraint, the retrieval analysis was designed to evaluate the sensitivity of the atmospheric interpretation to a range of fixed planetary masses.

4.6.1 Model grid and fixed-mass experiment

The absence of an independent planetary mass measurement from radial velocities makes the assumed planetary gravity an important part of the retrieval setup. Following the scale-height argument of [de Wit and Seager \(2013\)](#), the amplitude of transmission features depends on the planetary mass assumed in the retrieval. We therefore repeated the retrieval for six fixed masses: 0.60, 0.48, and 0.36 M_{Jup} for the conservative $N = 5, 4, 3$ cases, and 0.18, 0.15, and 0.11 M_{Jup} for the optimistic $N = 5, 4, 3$ cases. These masses are not independent dynamical measurements; rather, they are adopted as fixed inputs to assess how the atmospheric retrieval responds to the range of masses considered in the preceding analysis. Because the same transmission spectrum contributes to the underlying scale-height estimate, this experiment should be interpreted as a mass-sensitivity or feasibility analysis rather than as an independent determination of the planetary mass. This distinction is important because transmission spectra can exhibit degeneracies among planetary mass, atmospheric mean molecular weight, temperature, clouds, and composition ([Batalha et al., 2017a](#)).

For each mass scenario, we considered the four atmospheric model families listed in Table 4.6.1. In all cases, an isothermal temperature–pressure profile was adopted, with the atmosphere discretized into 100 pressure layers spanning 10^{-4} – 10^6 Pa and an H_2/He background atmosphere. The reference planetary radius and atmospheric temperature were retrieved as free parameters.

Table 4.6.1: Atmospheric retrieval model families used for the TOI-1019 b mass-sensitivity grid. Abundances are retrieved as constant-with-altitude log volume mixing ratios.

Model family	Free parameters	Active opacity species	Cloud treatment
Flat/cloudy	$R_p, T, \log X_{\text{H}_2\text{O}}, \log P_{\text{cloud}}$	H_2O	grey cloud deck
Free minimal	$R_p, T, \log X_{\text{H}_2\text{O}}, \log X_{\text{Na}}, \log X_{\text{TiO}}$	$\text{H}_2\text{O}, \text{Na}, \text{TiO}$	none
Free chemistry, no clouds	$R_p, T, \log X_i$ for $\text{H}_2\text{O}, \text{Na}, \text{TiO}, \text{VO}, \text{NaH}, \text{MgO}, \text{NH}_3$	$\text{H}_2\text{O}, \text{Na}, \text{TiO}, \text{VO}, \text{NaH}, \text{MgO}, \text{NH}_3$	none
Free chemistry + clouds	same free chemistry set plus $\log P_{\text{cloud}}$	$\text{H}_2\text{O}, \text{Na}, \text{TiO}, \text{VO}, \text{NaH}, \text{MgO}, \text{NH}_3$	grey cloud deck

The adopted planetary mass directly affects the atmospheric scale height,

$$H = \frac{k_B T}{\mu g}, \quad g = \frac{GM_p}{R_p^2}, \quad (4.6.1)$$

and therefore the amplitude of spectral features expected for a given temperature and mean molecular weight. For a reference radius of $R_p = 2.17 R_{\text{Jup}}$, the six tested masses correspond to surface gravities between 0.579 and 3.158 m s^{-2} and relative scale heights between 9.1 and 1.7 times that of a hypothetical $1 M_{\text{Jup}}$ planet with the same radius, temperature, and mean molecular weight (Table 4.6.2; Fig. 4.6.1). This range illustrates the sensitivity of the expected transmission-spectrum amplitude to the assumed planetary mass. At the same time, variations in the retrieved radius, temperature, chemical abundances, and cloud pressure can partially compensate for changes in surface gravity. The fixed-mass retrievals therefore provide a sensitivity analysis of the atmospheric interpretation rather than an independent constraint on the planetary mass.

Table 4.6.2: Physical scale implied by the fixed masses, using the TauREx reference radius $R_p = 2.17 R_{\text{Jup}}$. The scale-height factor assumes constant temperature and mean molecular weight and is normalized to a hypothetical $1 M_{\text{Jup}}$ case at the same radius.

Scenario	M_p [M_{Jup}]	R_p [R_{Jup}]	g [m s^{-2}]	ρ [g cm^{-3}]	$H/H_{1M_{\text{Jup}}}$
Opt.	0.11	2.17	0.579	0.014	9.09
Opt.	0.15	2.17	0.790	0.019	6.67
Opt.	0.18	2.17	0.947	0.023	5.56
Cons.	0.36	2.17	1.895	0.047	2.78
Cons.	0.48	2.17	2.527	0.062	2.08
Cons.	0.60	2.17	3.158	0.078	1.67

4.6.2 Spectral fits

Figure 4.6.2 shows the observed transmission spectrum and the highest-evidence retrieval at each fixed mass. Figure 4.6.3 shows the four atmospheric configurations at each mass. All model families reproduce the broad level of the optical spectrum within the present uncertainties. The differences among retrieval families are generally smaller than the point-to-point scatter in the data, indicating that the current spectrum has limited leverage to distinguish between the tested opacity and cloud prescriptions. The lower-mass cases naturally produce larger atmospheric scale heights; nevertheless, they can reproduce the observed spectrum through compensating changes in the retrieved atmospheric and reference-radius parameters.

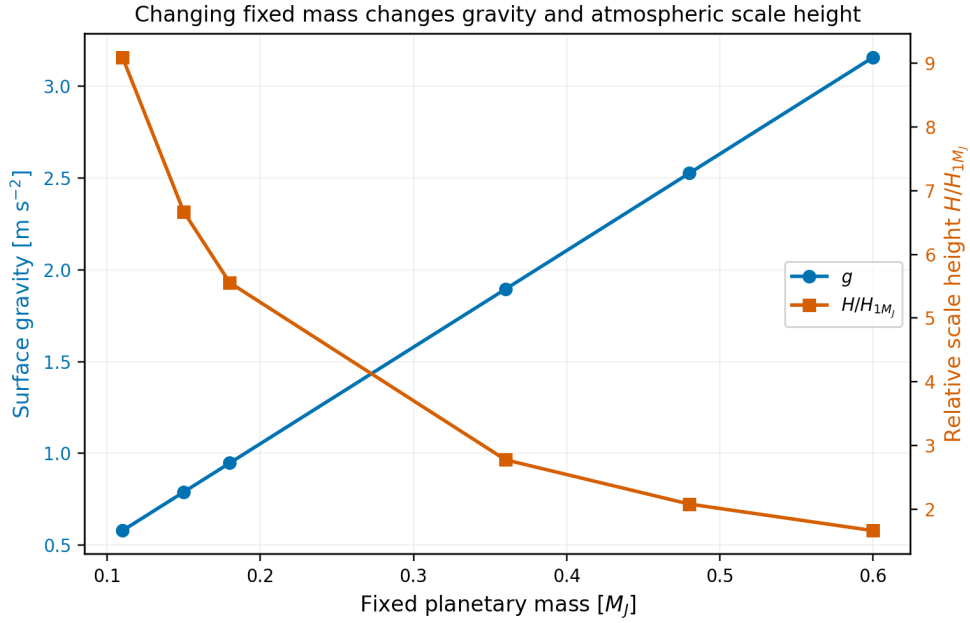


Figure 4.6.1: Surface gravity and relative scale height for the six fixed masses used in the retrieval grid. The scale-height factor is normalized to a $1 M_{Jup}$ planet at the same reference radius and assumes fixed temperature and mean molecular weight.

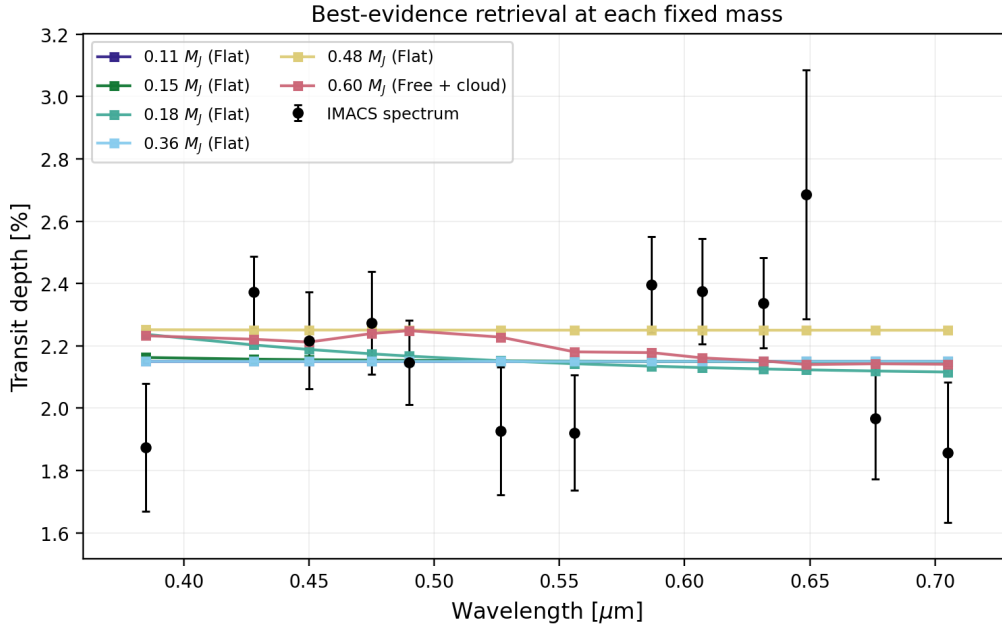


Figure 4.6.2: Observed IMACS transmission spectrum of TOI-1019 b compared with the best-evidence TauREx model at each fixed mass. Curves are plotted in transit-depth units and the square markers show the binned model values.

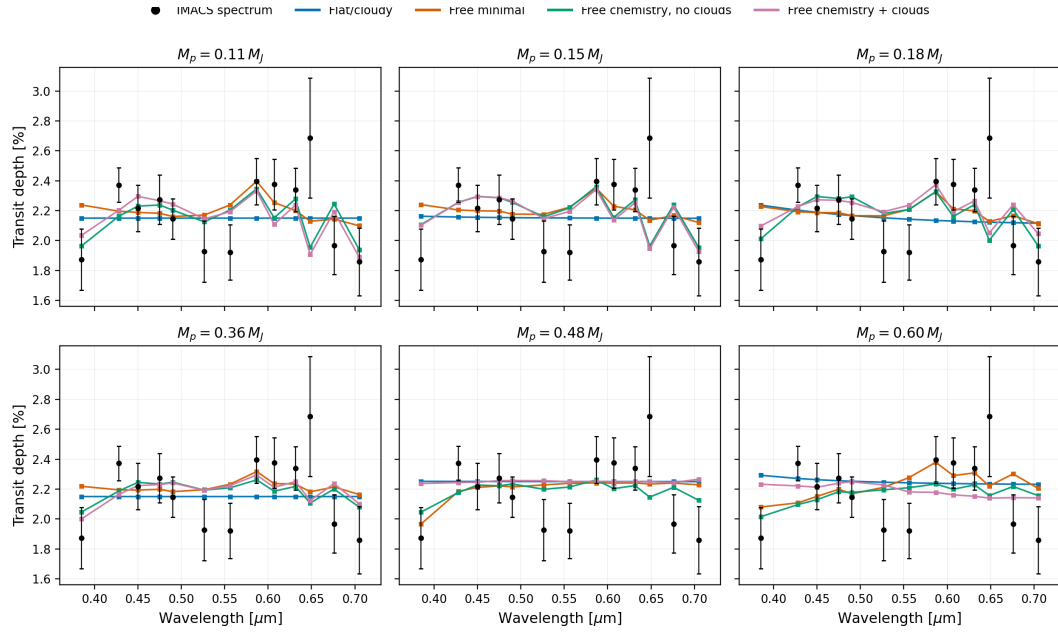


Figure 4.6.3: Retrieval spectra grouped by fixed mass. Each panel compares the four atmospheric model families at the same planetary mass. The overlap among model spectra illustrates that the current optical data do not uniquely select a chemical/cloud model.

4.6.3 Evidence ranking and mass feasibility

The full retrieval grid is summarized in Table 4.6.3. The highest evidence among the retrieval runs is obtained for the Free chemistry + clouds model at $M_p = 0.60 M_{\text{Jup}}$, with $\ln Z = 57.449 \pm 0.058$. However, the advantage over other conservative-mass solutions is small. For example, the difference between this model and the flat/cloudy model at $0.60 M_{\text{Jup}}$ is $\Delta \ln Z = 0.249$, which is not decisive on standard Bayes-factor scales (Kass and Raftery, 1995). Thus, although the maximum evidence occurs for a cloudy free-chemistry model, the data do not provide strong evidence that the additional chemical and cloud parameters are required.

The evidence trend is more informative when grouped by mass. The conservative cases, particularly $0.48\text{--}0.60 M_{\text{Jup}}$, yield the highest evidences, whereas the optimistic $0.11\text{--}0.18 M_{\text{Jup}}$ cases are systematically lower by about $0.7\text{--}1.0$ in $\ln Z$ for their best model. These differences remain weak in terms of Bayesian model comparison and do not by themselves exclude the lower-mass cases. However, the optimistic masses imply extremely low bulk densities ($\rho \simeq 0.014\text{--}0.023 \text{ g cm}^{-3}$ for $R_p \simeq 2.17 R_{\text{Jup}}$) and very large atmospheric scale heights. We therefore regard the

Table 4.6.3: TauREx/MultiNest retrieval grid for the six fixed masses inferred from the transmission-spectrum scale-height estimate. The quoted $\Delta \ln Z$ values are relative to the highest evidence among the 24 uploaded runs. Model definitions are given below the table.

Model	Scenario	N	M_p [M_{Jup}]	g [m s^{-2}]	$\ln Z$	$\Delta \ln Z$	Modes	Atmospheric setup
Flat/cloudy	Optimistic	3	0.11	0.579	56.461	-0.988	1	M1
Free minimal	Optimistic	3	0.11	0.579	55.125	-2.323	2	M2
Free chemistry, no clouds	Optimistic	3	0.11	0.579	55.324	-2.124	1	M3
Free chemistry + clouds	Optimistic	3	0.11	0.579	55.631	-1.818	1	M4
Flat/cloudy	Optimistic	4	0.15	0.790	56.663	-0.786	1	M1
Free minimal	Optimistic	4	0.15	0.790	55.585	-1.864	2	M2
Free chemistry, no clouds	Optimistic	4	0.15	0.790	55.998	-1.451	1	M3
Free chemistry + clouds	Optimistic	4	0.15	0.790	56.071	-1.378	1	M4
Flat/cloudy	Optimistic	5	0.18	0.947	56.744	-0.705	1	M1
Free minimal	Optimistic	5	0.18	0.947	55.621	-1.827	2	M2
Free chemistry, no clouds	Optimistic	5	0.18	0.947	56.047	-1.401	1	M3
Free chemistry + clouds	Optimistic	5	0.18	0.947	56.297	-1.151	1	M4
Flat/cloudy	Conservative	3	0.36	1.895	57.093	-0.355	1	M1
Free minimal	Conservative	3	0.36	1.895	56.348	-1.101	2	M2
Free chemistry, no clouds	Conservative	3	0.36	1.895	57.039	-0.409	1	M3
Free chemistry + clouds	Conservative	3	0.36	1.895	56.835	-0.613	1	M4
Flat/cloudy	Conservative	4	0.48	2.527	57.269	-0.180	1	M1
Free minimal	Conservative	4	0.48	2.527	56.929	-0.520	1	M2
Free chemistry, no clouds	Conservative	4	0.48	2.527	57.100	-0.349	1	M3
Free chemistry + clouds	Conservative	4	0.48	2.527	57.172	-0.277	1	M4
Flat/cloudy	Conservative	5	0.60	3.158	57.200	-0.249	1	M1
Free minimal	Conservative	5	0.60	3.158	57.227	-0.222	1	M2
Free chemistry, no clouds	Conservative	5	0.60	3.158	57.211	-0.238	1	M3
Free chemistry + clouds	Conservative	5	0.60	3.158	57.449	0.000	1	M4

Notes. M1: active species H_2O ; free parameters R_p/R_{Jup} , T , $\log X_{\text{H}_2\text{O}}$, and $\log P_{\text{cloud}}$. M2: active species H_2O , Na, TiO; free parameters R_p/R_{Jup} , T , $\log X_{\text{H}_2\text{O}}$, $\log X_{\text{Na}}$, and $\log X_{\text{TiO}}$. M3: active species H_2O , Na, TiO, VO, NaH, MgO, NH_3 ; free parameters R_p/R_{Jup} , T , $\log X_{\text{H}_2\text{O}}$, $\log X_{\text{Na}}$, $\log X_{\text{TiO}}$, $\log X_{\text{VO}}$, $\log X_{\text{NaH}}$, $\log X_{\text{MgO}}$, and $\log X_{\text{NH}_3}$. M4: same active species and free chemical abundances as M3, with the additional cloud parameter $\log P_{\text{cloud}}$.

optimistic masses as statistically compatible with the retrieval grid but physically extreme, pending an independent mass measurement. Within the tested grid, the conservative masses are consequently the more favourable and physically plausible solutions.

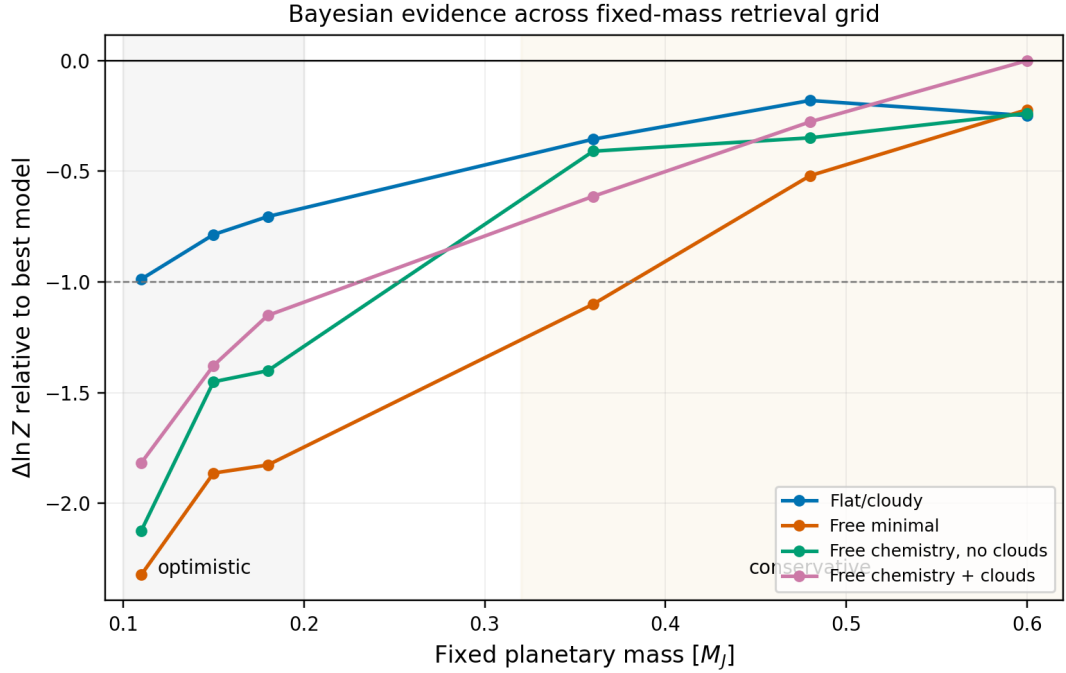


Figure 4.6.4: Bayesian evidence as a function of fixed planetary mass for the four atmospheric model families.

4.6.4 Posterior constraints and chemical interpretation

Posterior samples were read directly from the equal-weight MultiNest posterior files for each retrieval run. For the overplotted corner diagrams, we compare only parameters that are present in all relevant models: R_p , T , and $\log X_{\text{H}_2\text{O}}$ for the all-model comparison, and R_p , T , $\log X_{\text{H}_2\text{O}}$, and $\log P_{\text{cloud}}$ for the cloudy-model comparison. Full-dimensional posteriors are not overplotted across models with different parameter spaces; instead, the native-dimensional corner plots are provided separately for each retrieval run.

The posterior overlays (Figs. 4.6.7 and 4.6.8) show broad and overlapping distributions. In the flat/cloudy models, the H_2O abundance and cloud pressure are weakly constrained and coupled to the reference radius and temperature. In the free-chemistry models, the abundances of Na, TiO, VO, NaH, MgO, and NH_3

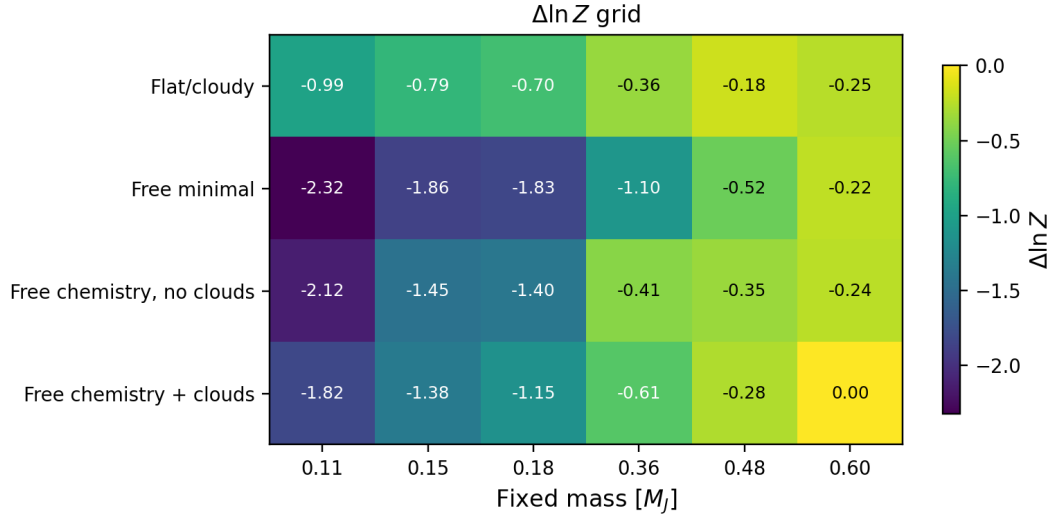


Figure 4.6.5: Grid of $\Delta \ln Z$ relative to the best run. The evidence mildly favours the conservative mass range, while model-family differences at a fixed mass remain small.

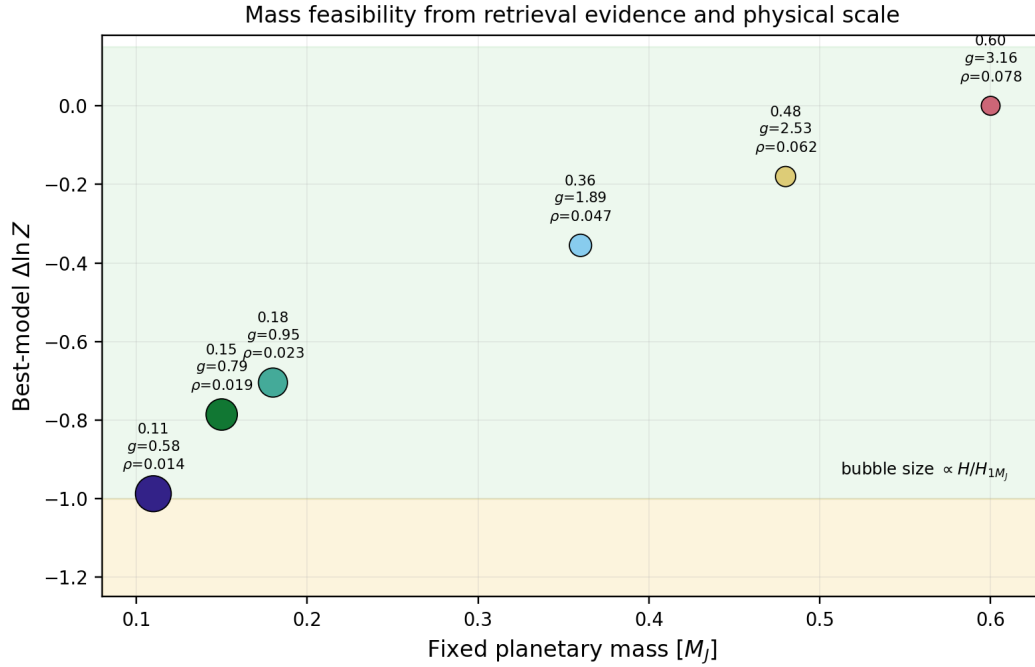


Figure 4.6.6: Mass feasibility summary. Points show the best-evidence model at each fixed mass; the vertical coordinate is $\Delta \ln Z$, labels give the corresponding gravity and bulk density, and marker size scales with the relative atmospheric scale height.

Table 4.6.4: Mass feasibility summary from the fixed-mass retrieval grid. The evidence assessment uses only the uploaded retrievals; it does not include a 1 M_{Jup} baseline.

Scenario	N	M_p [M_{Jup}]	Best model	$\ln Z$	$\Delta \ln Z$	g [m s^{-2}]	Assessment	Chemistry interpretation
Optimistic	3	0.11	Flat/cloudy	56.461	-0.988	0.579	compatible, lower evidence	Featureless/cloudy model is sufficient; no species is robustly distinguished
Optimistic	4	0.15	Flat/cloudy	56.663	-0.786	0.790	compatible, lower evidence	Featureless/cloudy model is sufficient; no species is robustly distinguished
Optimistic	5	0.18	Flat/cloudy	56.744	-0.705	0.947	compatible, lower evidence	Featureless/cloudy model is sufficient; no species is robustly distinguished
Conservative	3	0.36	Flat/cloudy	57.093	-0.355	1.895	preferred/compatible	Featureless/cloudy model is sufficient; no species is robustly distinguished
Conservative	4	0.48	Flat/cloudy	57.269	-0.180	2.527	preferred/compatible	Featureless/cloudy model is sufficient; no species is robustly distinguished
Conservative	5	0.60	Free chemistry + clouds	57.449	0.000	3.158	preferred/compatible	Complex chemistry and clouds are allowed, but not decisively required

span broad intervals, with no individual species showing a sufficiently constrained posterior or a decisive evidence gain to support a detection. We therefore do not claim a detection of any specific absorbing species or cloud deck from the present IMACS spectrum. The results are instead consistent with an H_2/He -dominated atmosphere over a range of fixed masses, while the current data are insufficient to distinguish between a featureless/cloudy continuum and more complex optical chemistry.

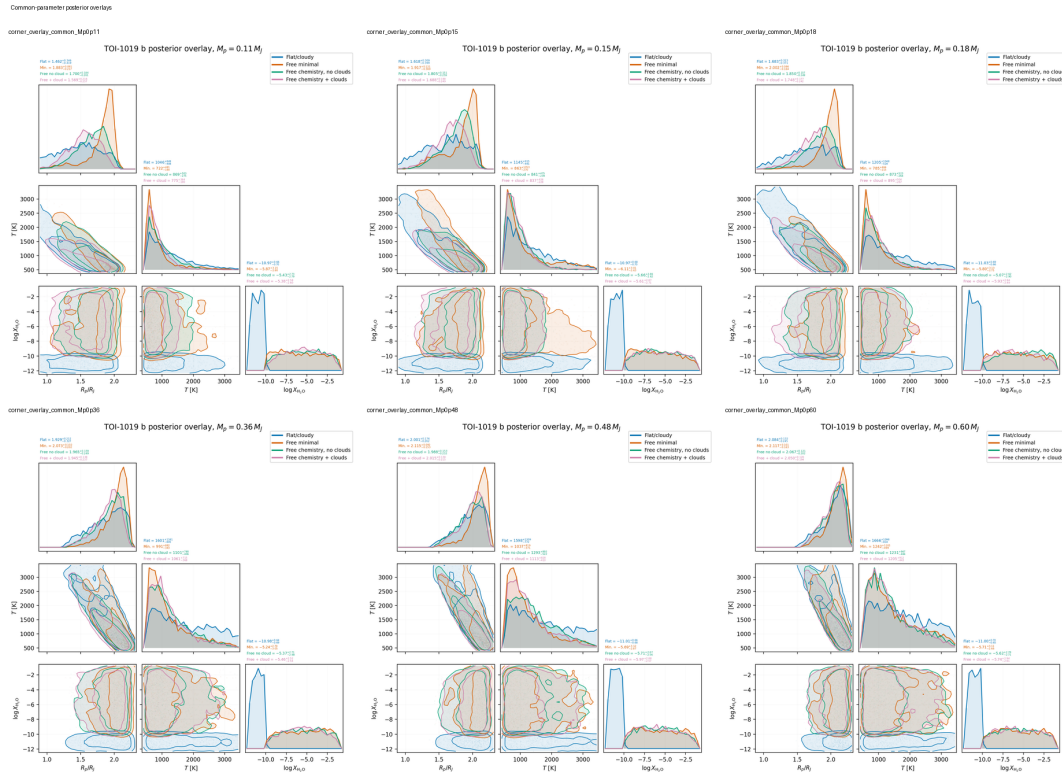


Figure 4.6.7: Overlaid posterior corner plots in the common parameter space R_p , T , and $\log X_{\text{H}_2\text{O}}$ for each fixed mass. For each atmospheric family, the samples, one-dimensional posterior distributions, filled contours, and contour lines use the same color.

4.6.5 Summary of the retrieval experiment

The six fixed-mass retrievals provide a controlled assessment of how the atmospheric interpretation changes across the range of masses considered in the preceding scale-height analysis. The retrieval grid shows that the assumed planetary mass strongly affects the inferred surface gravity and atmospheric scale height, while the optical spectrum remains compatible with multiple atmospheric

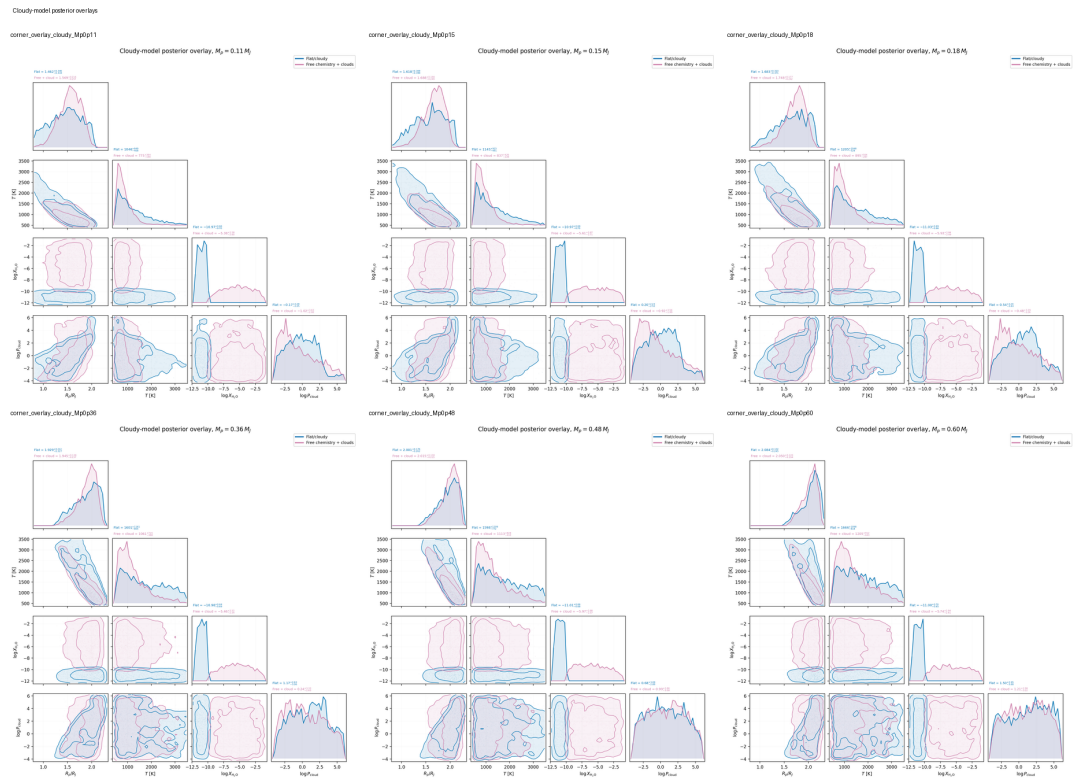


Figure 4.6.8: Overlaid posterior corner plots for the two cloudy configurations in the shared cloudy parameter space R_p , T , $\log X_{\text{H}_2\text{O}}$, and $\log P_{\text{cloud}}$. These plots compare only parameters present in both cloudy models.

Table 4.6.5: Posterior summaries for the best-evidence model at each fixed mass. Values are medians with 16–84% intervals from the equal-weight MultiNest posterior samples. Missing entries indicate parameters not present in that model.

M_p [M_{Jup}]	Scenario	Best model	R_p/R_{Jup}	T [K]	$\log X_{\text{H}_2\text{O}}$	$\log P_{\text{cloud}}$	$\log X_{\text{Na}}$	$\log X_{\text{TiO}}$	$\log X_{\text{VO}}$	$\log X_{\text{NH}_3}$
0.11	Optimistic	Flat/cloudy	$1.462^{+0.346}_{-0.419}$	1046^{+849}_{-408}	$-10.97^{+0.66}_{-0.70}$	$-0.17^{+2.28}_{-2.25}$	...	...	...	...
0.15	Optimistic	Flat/cloudy	$1.618^{+0.309}_{-0.399}$	1145^{+915}_{-491}	$-10.97^{+0.68}_{-0.70}$	$0.20^{+2.23}_{-2.52}$	...	...	...	...
0.18	Optimistic	Flat/cloudy	$1.683^{+0.323}_{-0.371}$	1205^{+1048}_{-528}	$-11.03^{+0.69}_{-0.66}$	$0.54^{+2.24}_{-2.63}$	...	...	...	...
0.36	Conservative	Flat/cloudy	$1.929^{+0.327}_{-0.176}$	1601^{+1161}_{-805}	$-10.98^{+0.64}_{-0.69}$	$1.17^{+3.06}_{-2.89}$	...	...	...	...
0.48	Conservative	Flat/cloudy	$2.001^{+0.176}_{-0.262}$	1598^{+1209}_{-772}	$-11.01^{+0.66}_{-0.68}$	$0.68^{+3.09}_{-2.89}$	...	...	...	...
0.60	Conservative	Free chemistry + clouds	$2.050^{+0.120}_{-0.194}$	1205^{+912}_{-443}	$-5.74^{+2.94}_{-2.61}$	$1.21^{+2.96}_{-3.22}$	$-5.36^{+2.61}_{-2.75}$	$-5.25^{+2.43}_{-2.69}$	$-6.43^{+3.26}_{-2.31}$	$-5.56^{+2.62}_{-2.59}$

configurations. The conservative 0.48–0.60 M_{Jup} cases yield the highest evidences among the tested masses, but the evidence differences are not sufficiently large to provide an independent constraint on the planetary mass. The posterior distributions remain broad, and no robust molecular detection is supported by the present data. The 0.48–0.60 M_{Jup} cases are therefore the most favourable within the tested grid, whereas the 0.11–0.18 M_{Jup} cases remain statistically compatible but imply extremely low bulk densities and large atmospheric scale heights. An independent radial-velocity mass measurement is required to determine whether the preferred region of the fixed-mass grid corresponds to the actual planetary mass.

4.7 Summary and Conclusions

In this chapter, we presented the first optical atmospheric characterization of the highly inflated hot Jupiter TOI-1019 b using transmission spectroscopy obtained with IMACS on the 6.5-m Magellan Baade Telescope. The analysis combined spectrophotometric transit observations with Bayesian atmospheric retrievals to investigate the atmospheric properties of the planet across the optical range. The resulting transmission spectrum provides new observational constraints on the atmosphere of TOI-1019 b, while also allowing us to assess how the atmospheric interpretation depends on the poorly constrained planetary mass.

The observed transmission spectrum shows wavelength-dependent variations across the optical range, but the present data do not provide sufficient evidence to uniquely identify the dominant opacity sources. The retrieval analysis shows that the spectrum can be reproduced by different atmospheric configurations, including models with atomic absorbers and grey cloud opacity, while the differences in Bayesian evidence between model families remain small. The posterior distributions are likewise broad, and no specific molecular or atomic species can be robustly detected from the current spectrum. These results indicate that the optical data alone are insufficient to distinguish between a relatively featureless or cloudy atmosphere and models allowing more complex optical chemistry.

A central result of this study is the strong dependence of the atmospheric interpretation on the assumed planetary mass. The fixed-mass retrieval grid demonstrates that changes in mass substantially modify the surface gravity and

atmospheric scale height, while variations in the retrieved radius, temperature, composition, and cloud properties can compensate for these changes and produce similarly acceptable spectral fits. Although the 0.48–0.60 M_{Jup} cases provide the most favourable solutions within the tested grid, the retrievals do not constitute an independent measurement of the planetary mass. The MassSpec analysis provides a complementary assessment of the same mass–scale-height dependence and therefore supports the interpretation that the planetary mass must be independently constrained before the atmospheric properties can be robustly interpreted. Future radial-velocity observations are consequently essential for breaking the present mass–atmosphere degeneracy.

Despite these limitations, TOI-1019 b remains a promising target for future atmospheric characterization. Its highly inflated radius and relatively low surface gravity make it particularly favourable for transmission spectroscopy, while its atmospheric interpretation would benefit substantially from an independent dynamical mass. Future radial-velocity observations, together with higher signal-to-noise transmission spectra extending over a broader wavelength range, would provide stronger constraints on the planetary mass, atmospheric composition, cloud properties, and scattering processes. Observations with facilities such as JWST could therefore help determine whether the spectral variations suggested by the current optical data correspond to specific atmospheric opacity sources. Improved constraints on both the interior and atmosphere of TOI-1019 b would also make the system a valuable target for investigating the mechanisms responsible for radius inflation and the long-term evolution of highly irradiated giant planets.

Beyond the characterization of an individual system, this study contributes to the broader understanding of the atmospheric diversity and evolution of hot Jupiters. As discussed in Chapter 2.3.4, atmospheric properties are connected to broader questions concerning planetary formation, migration, atmospheric evolution, and the radius inflation problem. While the present observations cannot distinguish between competing formation, migration, or inflation scenarios, they provide new observational constraints for an inflated giant planet whose atmospheric interpretation is strongly affected by the uncertainty in its planetary mass. Expanding the sample of well-characterized hot Jupiters, particularly through complementary measurements of their masses and atmospheres, is essential for identifying population-level trends and testing models of giant-planet evolution.

Overall, the results presented in this chapter establish TOI-1019 b as a valuable target for future studies of highly irradiated giant planets. The IMACS transmission spectrum provides the first optical atmospheric constraints for this system, while the retrieval experiments demonstrate the importance of obtaining an independent planetary mass before drawing stronger conclusions about its atmospheric composition and structure. Together with the physical characterization of TOI-6105 b and Gaia-7 b presented in the following chapter, this work contributes to the primary objective of this thesis: improving our observational understanding of the physical properties, atmospheric characteristics, and evolutionary processes governing close-in giant exoplanets.

Chapter 5

Unveiling the nature of gas giant planets in the first PLATO Field

5.1 Abstract

Hot Jupiters and Ultra-hot Jupiters represent some of the most extreme exoplanets currently known. Their intense stellar irradiation can significantly affect their atmospheric properties and internal structures, leading in many cases to inflated radii and low bulk densities that remain challenging to fully explain. Expanding the sample of well-characterized highly irradiated giant planets is therefore crucial for improving our understanding of planetary structure, evolution, and atmospheric properties. In this chapter, we present the confirmation of two giant planets with circular orbits around stars located in the first long-pointing PLATO field (LOPS2), the hot Jupiter TOI-6105 b and the Ultra-hot Jupiter *Gaia*-7b. Precise radial velocity (RV) observations using HARPS were collected over a span of four months, obtaining 14–18 spectra for each target. By jointly modeling these RVs, in combination with CORALIE RV data and both *TESS* and ground-based photometric light curves, we precisely determine the planetary parameters of each system. We confirm the planetary nature of both targets, obtaining precise orbital periods ($P \approx 3.1123$ d; $P \approx 1.5304$ d), radii ($R_p = 15.49 \pm 0.14 R_\oplus$; $R_p = 19.24 \pm 0.46 R_\oplus$), masses ($M_p = 249 \pm 8 M_\oplus$; $M_p = 486 \pm 22 M_\oplus$), equilibrium temperatures ($T_{\text{eq}} = 1559 \pm 10$ K; $T_{\text{eq}} = 2301 \pm 30$ K), and TSM values (165 ± 8 ; 61 ± 6) for TOI-6105 b and *Gaia*-7b, respectively. Our results confirm *Gaia*-7b as the seventh UHJ located in the first field of PLATO, while also

providing insights into the potential atmospheric characterization of TOI-6105 b with JWST due to its high TSM value.

5.2 Target selection

The first step of this work was to identify candidate giant exoplanets suitable for follow-up observations. We selected, from the catalog of TESS Objects of Interest (TOIs), candidate giant planets with $R_p > 8R_\oplus$ and estimated equilibrium temperatures of $T_{\text{eq}} > 1500$ K. This sample was then cross-matched with the coordinates of the PLATO LOPS2 field (Rauer et al., 2025; Nascimbeni et al., 2025). From the resulting sample, we selected systems with host stars having effective temperatures (T_{eff}) between 5000 and 6500 K and TESS magnitudes < 12.5 , observable from La Silla, and hosting giant planets with favourable prospects for atmospheric characterization with JWST.

The suitability of the selected giant planet candidates for atmospheric characterization with JWST was assessed using the Transmission Spectroscopic Metric (TSM; Kempton et al., 2018). We adopted a TSM value greater than 90 as an additional criterion for selecting promising targets. The TSM values for the candidate exoplanets were provided by the *TESS* atmospheric characterization working group and were calculated without an independent planetary-mass measurement. Applying this criterion resulted in an initial sample of seven candidate targets for follow-up observations.

The final stage of the target-selection procedure consisted of removing candidates identified as clear false positives, followed by statistical validation of the remaining seven promising candidates. This process resulted in the selection of two systems hosting statistically validated giant planets (see Section 5.5.1) that are potentially suitable for atmospheric studies with JWST: *Gaia*-7, hosting an ultra-hot Jupiter, and TOI-6105, hosting a hot Jupiter. At the time of the target selection, fewer than 30 confirmed planets in the LOPS2 field satisfied the adopted criteria for atmospheric characterization, with only one classified as an ultra-hot Jupiter (see Table 5.6.1). The relatively small number of suitable hot and ultra-hot Jupiters is unlikely to increase substantially through additional transit detections, given the high sensitivity of *TESS* and the existing ground-based surveys to planets in this region of parameter space.

5.3 Observations and data reduction

This section presents the observational data used in this work, including archival photometry and observations obtained through proposals submitted by our team.

Gaia-7 was first identified as a candidate transiting system (Gaia-TROI-029, source ID: 5578530470116727936) through *Gaia* DR3 photometry (Gaia Collaboration et al., 2016, 2023). The main parameters of the detected signal were reported in the *Gaia* DR3 Variable Sources: Planetary Transit candidate events table¹. These parameters are compatible with a transiting giant planet signal.

5.3.1 *TESS* photometry

Both targets were observed and identified as transiting planet candidates in *TESS* photometry. Specifically, TOI-6105 (TIC 182405015) was observed at 1800 s cadence in Sectors 7 and 8, at 600 s cadence in Sectors 34 and 35, and at 120 s cadence in Sectors 61, 62, 88, and 89. On the other hand, *Gaia*-7 (TIC 97279971; TOI-6409) was observed at 1800 s cadence in Sectors 6 and 7, at 600 s cadence in Sectors 33 and 34, at 200 s cadence in Sector 61, and at 120 s cadence in Sectors 87 and 88. The two-minute cadence light curves for both targets were reduced by the *TESS* SPOC pipeline, while the long-cadence light curves were normalized using the QLP for *Gaia*-7 and *TESS*-SPOC (Caldwell et al., 2020) for TOI-6105. Table 5.3.1 summarizes the *TESS* observations for both targets.

Table 5.3.1: Summarized observations from *TESS* for TOI-6105 and *Gaia*-7 (TOI-6409).

Target	Sector(s)	Source	Cadence
TOI-6105	7,8	TESS-SPOC	1800s
	34,35	TESS-SPOC	600s
	61, 62, 88, 89	SPOC	120s
TOI-6409	6,7	QLP	1800s
	33,34	QLP	600s
	61	QLP	200s
	87, 88	SPOC	120s

The *TESS* data products were downloaded from the Mikulski Archive for Space Telescopes (MAST)². For TOI-6105, I used the Pre-search Data Conditioning

¹https://gaia.aip.de/metadata/gaiadr3/vari_planetary_transit/

²<https://mast.stsci.edu/>

Simple Aperture Photometry (PDCSAP; [Smith et al. 2012](#); [Stumpe et al. 2012, 2014](#)) light curves. For *Gaia*-7, I used Kepler-Simple Amplitude Photometry (DET_FLUX, formerly KSPSAP; [Huang et al. 2020a,b](#)) for the QLP-processed light curves and PDCSAP for the SPOC-processed light curves. It is worth noting that the PDCSAP light curves are already corrected for stellar dilution.

All light-curves were further normalized and flattened using *wotan* ([Hippke et al., 2019](#)), following the procedure described in Chapter 4, Section 4.3.1. Such step was necessary to model the variability present in the *TESS* photometry and to enable an accurate transit depth estimation of both targets. For this, we masked out the transit signals using window sizes three times the predicted transit duration.

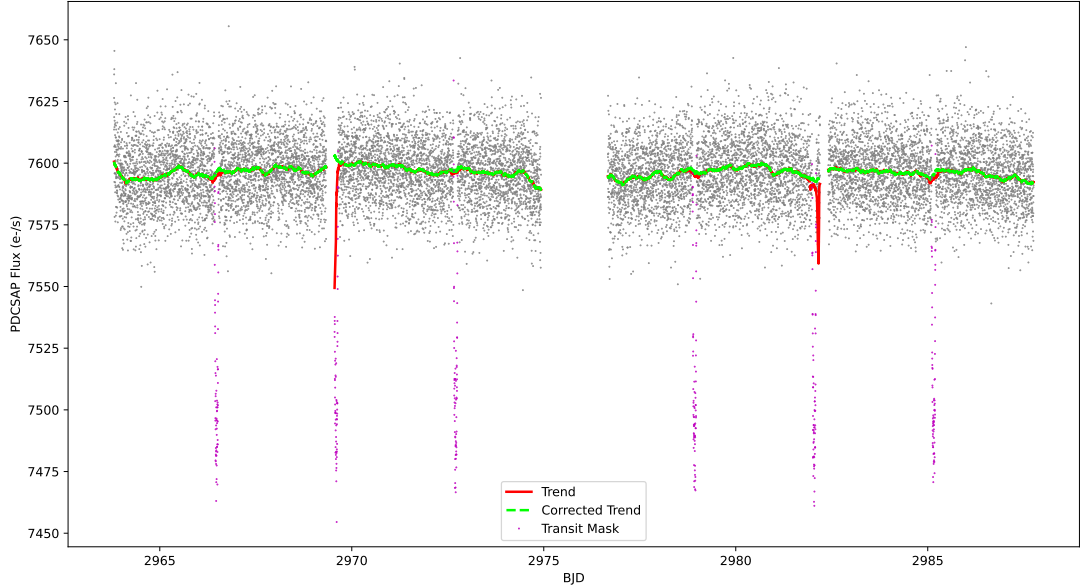


Figure 5.3.1: *TESS* PDCSAP light curve of TOI-6105 observed in Sector 61. The grey dots represent the observed dataset at 120 s cadence. Vertical lines mark the central transit times of TOI-6105 b, with the mask used for the flattening being highlighted in purple. The line dashed-line is the *wotan* biweight detrending model used to flatten the light curve.

5.3.2 Ground-based photometry

The *TESS* pixel scale is $\sim 21 \text{ pixel}^{-1}$, and the photometric apertures typically extend over roughly 1 arcminute, making contamination from nearby stars possible. To determine the true source of the transit signals detected by *TESS*, ground-based time-series follow-up photometry of the fields around TOI-6105 and *Gaia*-7 was obtained as part of the *TESS* Follow-up Observing Program (TFOP; [Collins,](#)

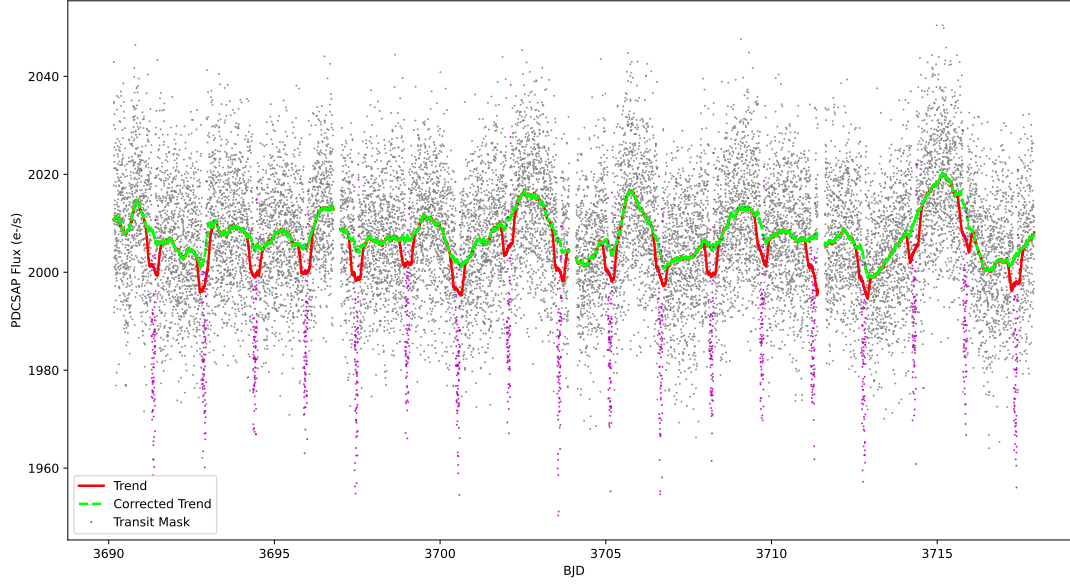


Figure 5.3.2: *TESS* PDCSAP light curve of *Gaia*-7/TOI-6409 observed in Sector 88. Same as in Figure 5.3.1, the gray dots represent the observed dataset at 120 s cadence. Vertical lines mark the central transit times of TOI-6409 b, with the mask used for the flattening being highlighted in purple. The lime dashed-line is the *wotan* biweight detrending model used to flatten the light curve.

2019)³. These observations also provide on-target measurements of the transit depths and additional constraints on the *TESS* ephemerides, while multi-band observations allow potential chromaticity of the transit depth to be assessed. The *TESS* Transit Finder, a customized version of the *Tapir* software package (Jensen, 2013), was used to schedule the transit observations. All ground-based photometric data were provided by Dr. Karen Collins and her collaborators.

5.3.2.1 TOI-6105 ground-based observations

The full transits of TOI-6105 b were observed on 2023 April 03 UTC in R_c band with the Hazelwood (Hwd) Observatory and on 2024 January 08 UTC in alternating Sloan g' and Sloan i' bands with the Perth Exoplanet Survey Telescope (PEST). Hazelwood Observatory is located near Churchill, Victoria, Australia. The 0.32 m telescope is equipped with a 2184×1472 SBIG STT3200 camera, with an image scale of 0.55 pixel^{-1} and a resulting 20×14 field of view. The *AstroImageJ* (Collins et al., 2017) package was used to calibrate the images and extract differential photometry. PEST is located near Perth, Australia. The

³<https://tess.mit.edu/followup>

0.3 m telescope is equipped with a 5544×3694 QHY183M camera, with an image scale of 07 pixel^{-1} and a resulting 32×21 field of view. A custom pipeline based on **C-Munipack**⁴ was used to calibrate the images and extract the differential photometry.

5.3.2.2 *Gaia*-7 ground-based observations

For *Gaia*-7b, a full transit was observed on 2023 December 19 UTC in Sloan g' band with the Hwd Observatory, although the observation had a limited pre-ingress baseline and data gaps caused by passing clouds. An ingress on 2023 December 14 UTC, as well as a full transit with a limited post-egress baseline on 2024 February 04 UTC, were observed in Sloan g' band with the Las Cumbres Observatory Global Telescope (LCOGT; [Brown et al., 2013](#)) 0.35 m network node at the South African Astronomical Observatory (SAAO) near Sutherland, South Africa. The 0.35 m Planewave Delta Rho 350 telescopes are equipped with a 9576×6388 QHY600 CMOS camera with an image scale of 073 pixel^{-1} , resulting in a 114×72 full field of view. We used the optional 30×30 sub-field of view to reduce the detector read-out time. The images were calibrated using the standard LCOGT BANZAI pipeline ([McCully et al., 2018](#)), and photometric data were extracted using **AstroImageJ**.

The ground-based photometric apertures excluded the flux from all *Gaia* DR3 neighboring sources bright enough to produce the transit signals detected within the *TESS* apertures, thereby confirming that the transit events occur on the target stars. The resulting light curves are modeled and presented in Section 5.5.

5.3.3 *HARPS* spectroscopic follow-up

Both TOI-6105 and *Gaia*-7 were observed with HARPS at the ESO 3.6 m telescope at La Silla Observatory ([Mayor et al., 2003](#)). The observations were obtained between December 2024 and March 2025 under proposal 114.27NN (PI: Á. Llancaqueo). The observations obtained in December 2024 were performed in Visitor Mode by the author, while the remaining observations were obtained in Service Mode. A total of 18 spectra were obtained for TOI-6105, with individual exposure times of 900 s, while 14 spectra were obtained for *Gaia*-7, with individual

⁴<http://c-munipack.sourceforge.net>

exposure times of 1800 s. The spectra cover the wavelength range 378–691 nm at a resolving power of $R \sim 115,000$.

The observations were obtained using the standard high-accuracy mode, with a 1'' science fiber centered on the target and fiber B positioned on the sky (Mayor et al., 2003). As a precaution against contamination and unfavorable observing conditions, observations were avoided when the absolute difference between the systemic radial velocity of the target and the barycentric Earth radial velocity correction was lower than 15 km s⁻¹, or when the fractional lunar illumination exceeded 0.9 (e.g., Malavolta et al., 2017; Roy et al., 2020).

The general HARPS observational setup, data reduction, radial velocity extraction, and spectroscopic activity diagnostics are described in Chapter 3, Section 3.2. The resulting radial velocities and activity indicators were used as the spectroscopic dataset for the subsequent analysis of both targets. The HARPS radial velocities were combined with the available transit and photometric data in the global modeling described in Section 3.4.2, allowing us to constrain the physical and orbital properties of TOI-6105 b and *Gaia*-7b, including their planetary masses and orbital parameters.

5.3.4 CORALIE data

Gaia-7 was observed with the CORALIE high-resolution, fibre-fed échelle spectrograph mounted on the Swiss 1.2 m Euler telescope at La Silla Observatory (Queloz et al., 2001) between 2022 October 13 and 2023 June 7. A total of 25 RV measurements were obtained with exposure times of 1800 s, resulting in a median signal-to-noise ratio (S/N) of 8 per pixel near 550 nm. The spectra were reduced with the standard CORALIE data reduction pipeline, and the radial velocities were derived through cross-correlation with a G2 binary mask (Baranne et al., 1996; Pepe et al., 2002). The CORALIE RVs were combined with the HARPS measurements in the global modeling described in Section 3.4.2 and are shown together with the HARPS data in Figure 5.5.3b. These data were provided by Dr. Angelica Psaridi and her collaborators.

5.4 Stellar parameters

The stellar parameters of TOI-6105 and *Gaia*-7 were determined by combining photometric, astrometric, and spectroscopic observations with additional ancillary data. The analysis consisted of two main steps: the determination of the atmospheric parameters from the co-added HARPS spectra, followed by the estimation of the stellar radii, masses, and ages using the infrared flux method (IRFM) and isochrone fitting.

The first step in the analysis was to produce a co-added spectrum using all the available HARPS observations. The procedure adopted for the spectral co-addition is described in [Mantovan et al. \(2026\)](#), where a similar analysis was applied to the HJ TOI-159 b using both IMACS and HARPS observations.

5.4.1 Atmospheric parameters

The atmospheric parameters of both stars were first determined following the methodology introduced in [Villanova et al. \(2019\)](#). This analysis provides the effective temperature T_{eff} , surface gravity $\log g$, microturbulent velocity ξ , and iron abundance $[\text{Fe}/\text{H}]$.

For each star, the initial atmospheric parameters were assumed to be $T_{\text{eff}} = 6500$ K, $\log g = 4.3$ dex, and $\xi = 1.50$ km s⁻¹. Atmospheric models were calculated using the ATLAS9 code ([Kurucz, 1970](#)), adopting these initial values and $[\text{Fe}/\text{H}] = 0$. The values of T_{eff} , $\log g$, and ξ were then iteratively adjusted, recalculating the atmospheric models at each step. The effective temperature was constrained by removing trends between abundance and excitation potential, while ξ was determined by removing trends between abundance and reduced equivalent width. The surface gravity was constrained by requiring ionization equilibrium between Fe I and Fe II. Approximately 80 Fe I lines and 7 Fe II lines were used for this analysis, with their equivalent widths measured by Gaussian fits.

The $[\text{Fe}/\text{H}]$ value of the atmospheric model was updated at each iteration according to the resulting abundance analysis. The local thermodynamic equilibrium program MOOG ([Sneden, 1973](#)) was used for the abundance determination.⁵ Non-local thermodynamic equilibrium (NLTE) corrections for the Fe I and Fe II

⁵<https://www-as-utexas-edu.translate.goog/chris/moog.html>

Table 5.4.1: Stellar properties of TOI-6105 and *Gaia*-7.

Parameter	TOI-6105	<i>Gaia</i> -7	Reference
α (J2000)	08:14:37.699	07:05:48.036	<i>Gaia</i> DR3
δ (J2000)	−41:09:22.311	−35:15:22.171	<i>Gaia</i> DR3
μ_α (mas yr ^{−1})	−19.415 ± 0.013	−2.681 ± 0.011	<i>Gaia</i> DR3
μ_δ (mas yr ^{−1})	14.291 ± 0.014	5.087 ± 0.013	<i>Gaia</i> DR3
RV (km s ^{−1})	28.82 ± 0.39	41.60 ± 1.17	<i>Gaia</i> DR3
π (mas)	3.735 ± 0.012	1.410 ± 0.012	<i>Gaia</i> DR3
V (mag)	11.304 ± 0.01	12.77 ± 0.05	Henden et al. (2016)
<i>G</i> (mag)	11.1830 ± 0.0087	12.635 ± 0.026	<i>Gaia</i> DR3
<i>G</i> _{BP} − <i>G</i> _{RP} (mag)	0.697	0.762	<i>Gaia</i> DR3
<i>J</i> (mag)	10.282 ± 0.026	11.639 ± 0.024	2MASS
<i>H</i> (mag)	10.058 ± 0.023	11.403 ± 0.022	2MASS
<i>K</i> (mag)	10.029 ± 0.023	11.359 ± 0.021	2MASS
<i>T</i> _{eff} (K)	6133 ± 23	6194 ± 32	Spec; Sect. 5.4.1
[Fe/H] (dex)	−0.07 ± 0.01	0.24 ± 0.01	Spec; Sect. 5.4.1
log <i>g</i>	4.15 ± 0.03	4.01 ± 0.03	Spec; Sect. 5.4.1
ξ (km s ^{−1})	1.12 ± 0.04	1.25 ± 0.04	Spec; Sect. 5.4.1
<i>T</i> _{eff} (K)	6133 ⁺²³ _{−24}	6201 ⁺³⁶ _{−30}	SED; Sect. 5.4.2
[Fe/H] (dex)	−0.07 ± 0.01	0.11 ^{+0.17} _{−0.02}	SED; Sect. 5.4.2
log <i>g</i>	4.32 ± 0.01	4.09 ^{+0.02} _{−0.04}	SED; Sect. 5.4.2
Luminosity (L _⊙)	1.78 ± 0.03	4.03 ^{+0.18} _{−0.12}	Sect. 5.4.2
Radius (R _⊙)	1.19 ± 0.01	1.74 ± 0.04	Sect. 5.4.2
Mass (M _⊙)	1.08 ± 0.02	1.37 ^{+0.05} _{−0.10}	Sect. 5.4.2
Density ($\rho_\odot$)	0.65 ± 0.01	0.25 ± 0.02	Sect. 5.4.2
Age (Gyr)	4.1 ± 0.3	2.5 ^{+1.0} _{−1.6}	Sect. 5.4.2
Distance (pc)	267.745 ± 0.8674	709.32 ± 5.8364	<i>Gaia</i> DR3

lines (Bergemann et al., 2012) were also considered. These corrections were obtained from the MPIA database.⁶ The resulting spectroscopic parameters are reported in Table 5.4.1.

5.4.2 Infrared flux method and isochrone fitting

The stellar radius and mass of TOI-6105 and *Gaia*-7 were determined by our collaborator from their spectroscopic atmospheric parameters, using a customized version of a code that incorporates the infrared flux method (IRFM, Blackwell and Shallis, 1977; Stassun et al., 2017) and isochrone fitting (MCMCI code, Bonfanti

⁶https://nlte.mpia.de/gui-siuAC_secE.php

and Gillon, 2020). The stellar angular diameter and T_{eff} were computed using known relations and the apparent bolometric flux. The atmospheric parameters were then used as priors to construct a spectral energy distribution (SED) from stellar atmospheric models (from the ATLAS catalogues, Castelli and Kurucz, 2003), corrected for extinction (Bovy et al., 2016; Green et al., 2019). The bolometric flux was derived by comparing synthetic photometry computed from the SED with observational data from the *Gaia* G , G_{BP} , G_{RP} , 2MASS J , H , K , and WISE W1 and W2 bandpasses. We then estimated $R_{\star}$ by converting the stellar angular diameter using the offset-corrected *Gaia* Early Data Release 3 parallax (Lindgren et al., 2021). With $R_{\star}$ as input, we determined the isochronal mass $M_{\star}$ and age $t_{\star}$ through the isochrone placement algorithm (Bonfanti et al., 2015), which interpolates the parameters within precomputed grids of PARSEC v1.2S (Marigo et al., 2017) isochrones and tracks. The resulting values are reported in Table 5.4.1.

5.4.3 Independent Spectral Energy Distribution

As an independent determination of the basic stellar parameters, an analysis of the broadband spectral energy distribution (SED) of the star together with the *Gaia* DR3 parallax was performed by an external collaborator (with no systematic offset applied; see, e.g., Stassun and Torres, 2021), in order to determine an empirical measurement of the stellar radius, following the procedures described in Stassun and Torres (2016); Stassun et al. (2017, 2018). He pulled the JHK_S magnitudes from 2MASS, the $G_{\text{BP}}G_{\text{RP}}$ magnitudes from *Gaia*, and the W1–W4 magnitudes from WISE. He also utilized the absolute flux-calibrated spectrophotometry from *Gaia*. Together, the available photometry spans the full stellar SED over the wavelength range 0.4–20 μm (see Figures 5.4.1a and 5.4.1b).

As a further step, he performed a fit using PHOENIX stellar atmosphere models (Husser et al., 2013), with the effective temperature (T_{eff}), surface gravity ($\log g$), and metallicity ($[\text{Fe}/\text{H}]$) adopted from the spectroscopic analysis. The extinction, A_V , was limited to maximum line-of-sight value from the Galactic dust maps of Schlegel et al. (1998). The resulting fits for TOI-6105 and *Gaia*-7 have a reduced χ^2 of 1.6 and 1.7, respectively, with a best-fit $A_V = 0.05 \pm 0.05$ and 0.28 ± 0.03 , respectively. Integrating the (unreddened) model SED gives the bolometric flux at Earth, $F_{\text{bol}} = 7.93 \pm 0.18 \times 10^{-10}$ and $2.539 \pm 0.059 \times 10^{-10}$

$\text{erg s}^{-1} \text{ cm}^{-2}$, respectively. Taking the F_{bol} together with the *Gaia* parallax directly gives the bolometric luminosity, $L_{\text{bol}} = 1.773 \pm 0.042 L_{\odot}$ and $3.983 \pm 0.098 L_{\odot}$, respectively. The stellar radius follows from the Stefan-Boltzmann relation, giving $R_{\star} = 1.181 \pm 0.017 R_{\odot}$ and $1.735 \pm 0.031 R_{\odot}$, respectively. In addition, the stellar mass from the empirical relations of [Torres et al. \(2010\)](#) was estimated, giving $M_{\star} = 1.15 \pm 0.07 M_{\odot}$ and $1.38 \pm 0.08 M_{\odot}$, respectively. The results from this independent analysis are shown in Table 5.4.2.

Table 5.4.2: Stellar properties of TOI-6105 and *Gaia*-7 derived from the additional SED analysis.

Parameter	TOI-6105	<i>Gaia</i> -7	Reference
Reduced χ^2	1.6	1.7	-
Extinction (A_V mag)	0.05 ± 0.05	0.28 ± 0.03	-
Bolometric Flux ($10^{-10} \text{ erg s}^{-1} \text{ cm}^{-2}$)	7.93 ± 0.18	2.539 ± 0.059	-
Luminosity ($L_{\odot}$)	1.773 ± 0.042	3.983 ± 0.098	via $F_{\text{bol}} + \text{plx}$
Radius ($R_{\odot}$)	1.181 ± 0.017	1.735 ± 0.031	via Stefan-Boltzmann relation
Mass ($M_{\odot}$)	1.15 ± 0.07	1.38 ± 0.08	Torres et al. (2010)

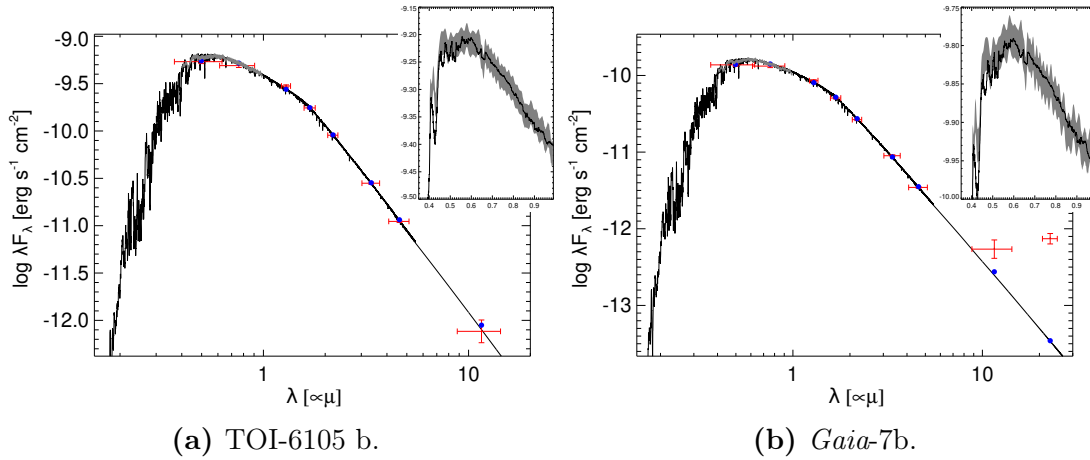


Figure 5.4.1: Spectral energy distributions of TOI-6105 (left) and *Gaia*-7 (right). Red symbols represent the observed photometric measurements, where the horizontal bars represent the effective width of the passband. Blue symbols are the model fluxes from the best-fit PHOENIX atmosphere model (black). The *Gaia* spectrophotometry is overlaid as the gray swathe, also in the inset plot.

5.5 Analysis

This section presents the analysis performed on the photometric and spectroscopic RV data obtained for both targets. The analysis includes the probabilistic

validation of each candidate, the joint modeling of the photometric and RV data, and an independent phase-folding analysis using the *Gaia* and *TESS* data for *Gaia*-7b.

5.5.1 Probabilistic validation and blends exclusion

A crucial step in the confirmation of candidate exoplanets is their statistical validation. In this work, our team and I performed a probabilistic validation analysis following a procedure similar to that described in Chapter 4.2.1. First, we examined the *Gaia* DR3 photometry to identify any *Gaia* source within the *TESS* PSF capable of mimicking the observed transit signal. In combination with the ground-based follow-up observations presented in Section 5.3, this analysis showed that none of the neighboring sources could reproduce the detected transit signal. We then used the **VESPA**⁷ software (Morton, 2012) to rigorously quantify the False Positive Probability (FPP) of each candidate, following the procedure adopted in Mantovan et al. (2022). Both targets have an extremely low ($< 1\%$) FPP, which statistically validates their planetary nature. This validation was an important basis for the follow-up observations presented in Section 5.3 and the joint modeling described in Section 5.5.2, which further confirmed the planetary nature of the systems subsequently referred to as TOI-6105 b and *Gaia*-7b.

5.5.2 Joint TESS, ground-based photometry, CORALIE, and HARPS RV modeling

To characterize the properties of TOI-6105 b and *Gaia*-7b, we simultaneously modeled the transits observed by *TESS*, the ground-based photometric data, and the HARPS RV time series. For *Gaia*-7b, the available CORALIE RV data were also included in the joint modeling. I conducted the analysis in a Bayesian framework using PyORBIT⁸ (Malavolta et al., 2016, 2018). Each transit was simultaneously modeled with the BATMAN code (Kreidberg, 2015) by fitting the following parameters: the reference transit time (T_0), the impact parameter (b), the orbital period (P_{orb}), the stellar density (ρ_*), the RV semi-amplitude (K), the quadratic limb-darkening (LD) coefficients u_1 and u_2 , adopting the LD parameterization introduced by Kipping (2013), the systemic RV offset,

⁷<https://github.com/timothymorton/VESPA>

⁸<https://github.com/LucaMalavolta/PyORBIT>

and a jitter term added in quadrature to the photometric errors to account for effects not captured by the model (e.g., short-term stellar activity) or potential underestimation of the error bars. Both the orbital periods and RV signals were fitted in linear space.

Gaussian priors were imposed on the LD coefficients u_1 and u_2 . As in Chapter 4.5.2, these coefficients were estimated using PyLDTk⁹ (Husser et al., 2013; Parviainen and Aigrain, 2015), applying the specific photometric filters used during the observations, and were then used as Gaussian priors. The Python code employed to estimate the LD coefficients for TOI-6105 and *Gaia*-7 is provided in Appendices A2.3 and A2.4, respectively. A value of 0.1 was added in quadrature to their associated Gaussian uncertainties to account for the known underestimation by the models. Finally, I imposed a Gaussian prior on the stellar density and uniform priors on P_{orb} and T_0 .

The phase-folded transit photometry for all *TESS* sectors and ground-based observations of TOI-6105 b and *Gaia*-7b is shown in Figures 5.5.1 and 5.5.2, respectively. Figures 5.5.3a and 5.5.3b show the respective RV models for the two targets.

5.5.3 Orbital modeling comparison

The joint analysis described in the previous section was performed for both targets under two orbital configurations. In the first case, the eccentricity was allowed to vary freely, while in the second case a circular orbit was assumed. For the orbital modeling, the Eastman2013_Tcent (Eastman et al., 2013) parametrization was adopted in both cases, using the time of inferior conjunction as the reference orbital epoch. In the eccentric model, the orbital configuration was described through the eccentricity and argument of periastron, while the circular model fixed $e = 0$.

To determine which orbital configuration was statistically preferred, we compared the Bayesian Information Criterion (BIC; Schwarz, 1978), defined as

$$\text{BIC} = k \ln(n) - 2 \ln(\hat{L}),$$

⁹<https://github.com/hpparvi/ldtk>

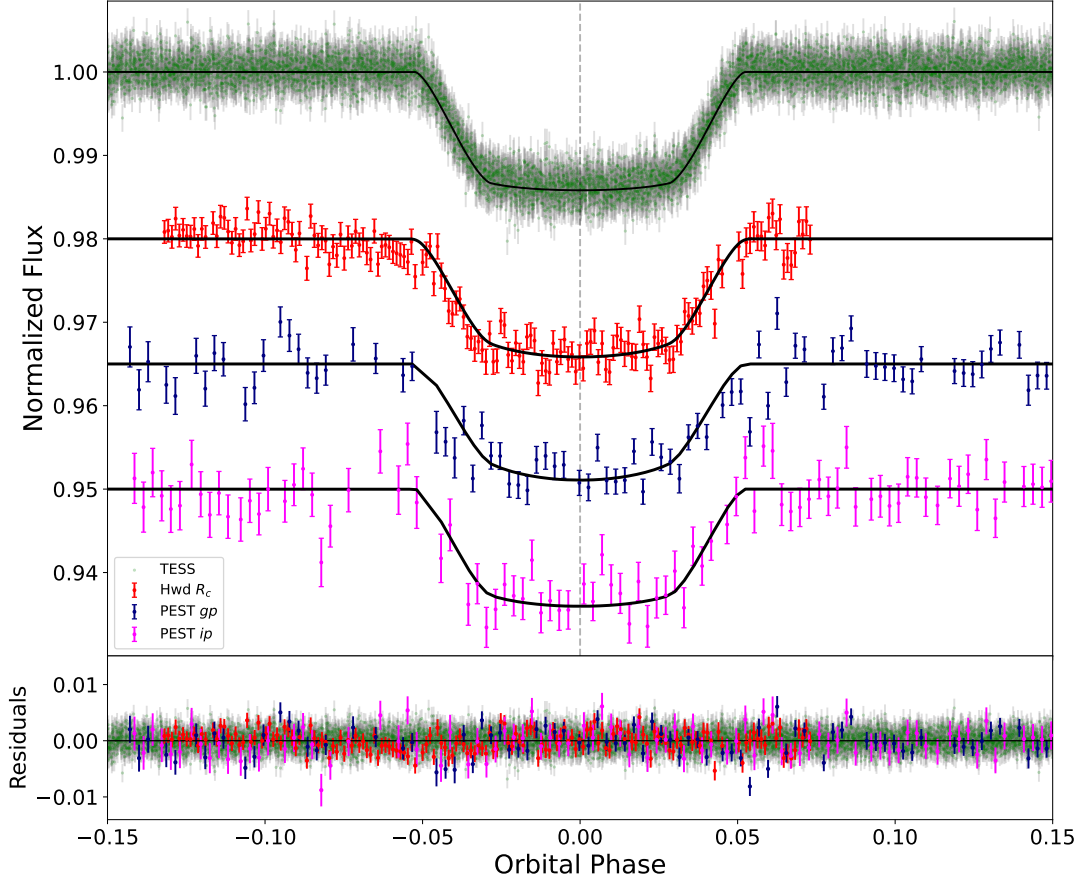


Figure 5.5.1: Photometric modeling of TOI-6105 b planetary signal. *Top panel:* *TESS* (green points) and ground-based photometry (Hwd R_c band in red, PEST gp band in navy, and PEST ip band in magenta) phase-folded transits of TOI-6105 b together with *TESS* transit model (black line). *Bottom panel:* Residuals of the fit.

where k is the number of free parameters, n is the number of observations, and $\hat{L}$ is the maximum likelihood. Thus, a lower BIC indicates a preferred model, while the difference between two models can be expressed as $\Delta\text{BIC}_{21} = \text{BIC}_2 - \text{BIC}_1$, where model 2 corresponds to the circular orbit and model 1 to the eccentric orbit. Consequently, negative values indicate a preference for the circular model.

For TOI-6105 b, the circular and eccentric models used 27 and 29 free parameters, respectively, while fitting the same 19,821 photometric and radial-velocity measurements. The additional parameters in the eccentric model were the two quantities used to describe the eccentric orbital configuration. Using the likelihood-based BIC, the circular model is favored over the eccentric model by $\Delta\text{BIC}_{21} \simeq -10$. The value of $\Delta\text{BIC}_{21} = -18$ reported in the published analysis was obtained from the posterior-based BIC reported by PyORBIT; however, the standard BIC

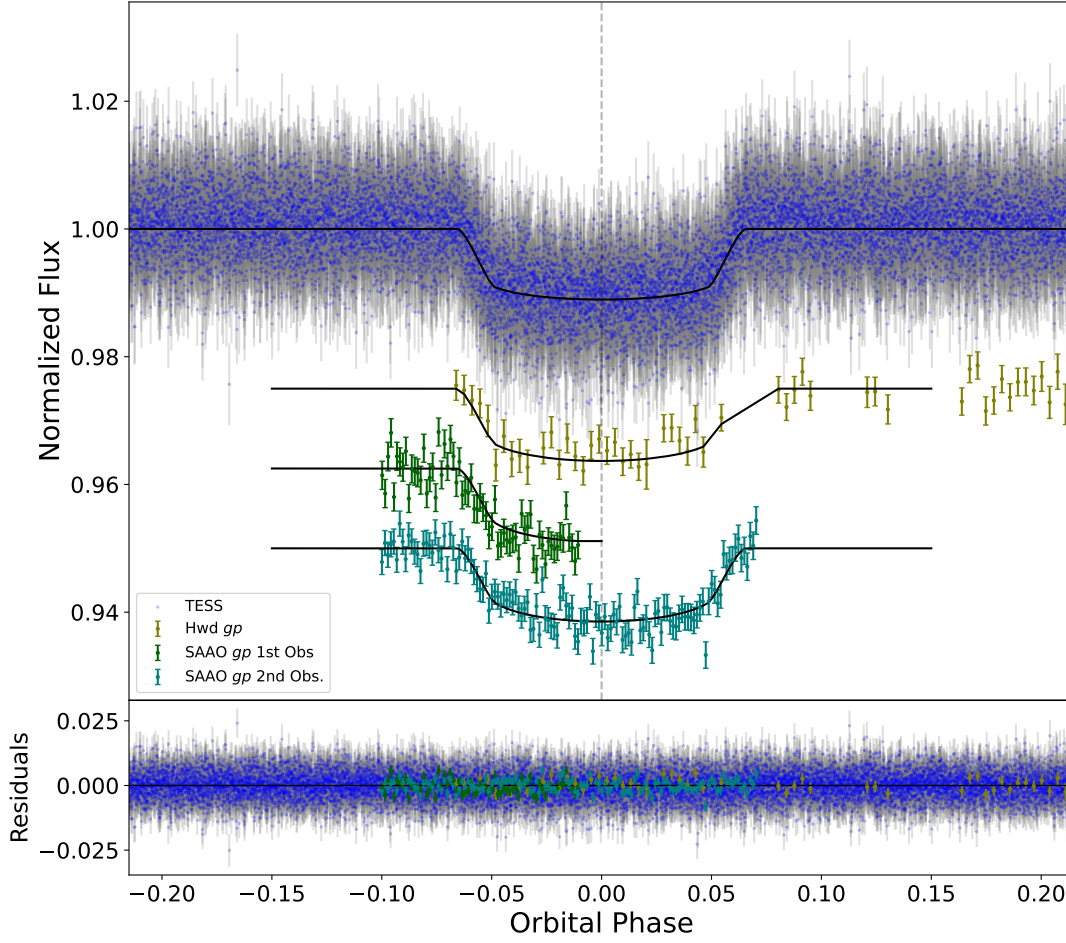


Figure 5.5.2: Same as Figure 5.5.1, but for *Gaia*-7b with its respective ground-based photometry instruments (Hwd and SAAO) and different colors.

is defined in terms of the likelihood. In either case, the comparison favors the simpler circular model.

The eccentric model yielded $e = 0.036^{+0.011}_{-0.011}$ and $\omega = 73^{+17}_{-16}$ degrees. This value of e formally satisfies the Lucy–Sweeney criterion (Lucy and Sweeney, 1971), which considers an eccentricity significant when $e > 2.5\sigma_e$. However, the BIC comparison does not support the additional complexity of the eccentric model. Moreover, the joint model already includes dataset-dependent jitter terms to account for additional scatter not captured by the deterministic transit and radial-velocity models. Therefore, the apparent preference for a small non-zero eccentricity should not be interpreted as a robust detection of orbital eccentricity. Instead, the results are consistent with a low-eccentricity orbit and do not provide sufficient evidence to reject the circular configuration.

Table 5.5.1: Priors and outcomes of the joint spectroscopic and photometric modeling of TOI-6105 b and *Gaia*-7b.

Planetary parameters		TOI-6105 b		<i>Gaia</i> -7b	
Parameter	Unit	Prior	Value	Prior	Value
Orbital period (P_{orb})	days	$\mathcal{U}(3.10, 3.12)$	3.1122944 ± 0.0000003	$\mathcal{U}(1.52, 1.54)$	1.5304231 ± 0.0000004
Central time of transit (T_0)	BTJD	$\mathcal{U}(3727, 3730)$	3728.99163 ± 0.00010	$\mathcal{U}(2579, 2581)$	2580.26164 ± 0.00023
Scaled semi-major axis ($\frac{a}{R_*}$)		...	7.86 ± 0.03	...	3.63 ± 0.07
Orbital semi-major axis (a)	AU	...	0.0428 ± 0.0003	...	0.0293 ± 0.0009
Orbital inclination (i)	deg	...	84.51 ± 0.05	...	81.29 ± 0.07
Orbital eccentricity (e)		0.0	0.0	0.0	0.0
Impact parameter (b)		$\mathcal{U}(0, 1)$	0.753 ± 0.004	$\mathcal{U}(0, 1)$	0.549 ± 0.030
Planet/star radius ratio ($\frac{R_p}{R_*}$)		$\mathcal{U}(0, 0.5)$	0.1193 ± 0.0003	$\mathcal{U}(0, 0.5)$	0.1013 ± 0.0007
Argument of pericenter (ω)	deg	...	90	...	90
Mean longitude (L)	deg	...	227.862 ± 0.02	...	173.7 ± 0.1
Transit duration (T_{14})	days	...	0.1051 ± 0.0003	...	0.1312 ± 0.0008
Planetary radius (R_p)	$R_{\oplus}$	...	15.49 ± 0.14	...	19.24 ± 0.46
Planetary radius (R_p)	R_j	...	1.382 ± 0.012	...	1.716 ± 0.041
Planetary mass (M_p)	M_j	...	0.783 ± 0.025	...	1.528 ± 0.069
Planetary mass (M_p)	$M_{\oplus}$	...	249 ± 8	...	486 ± 22
Planetary density (ρ_p)	g/cm^3	...	0.37 ± 0.02	...	0.38 ± 0.03
RV semi-amplitude (K)	m/s	$\mathcal{U}(0.01, 2000)$	103 ± 3	$\mathcal{U}(0.01, 2000)$	$215.7^{+5.7}_{-5.3}$
Stellar parameters		TOI-6105		<i>Gaia</i> -7	
Parameter	Unit	Prior	Value	Prior	Value
Density (ρ_*)	$\rho_{\odot}$	$\mathcal{N}(0.65, 0.01)$	0.674 ± 0.009	$\mathcal{N}(0.25, 0.02)$	0.274 ± 0.016

For *Gaia*-7b, the same comparison between circular and eccentric configurations also favored the circular model, with $\Delta\text{BIC}_{21} = -31$ as reported in the published analysis. The eccentric fit yielded $e = 0.022^{+0.020}_{-0.014}$, which does not satisfy the Lucy–Sweeney criterion. We therefore adopted the circular configuration as the reference model for the subsequent characterization of both planets. The resulting planetary and orbital parameters are reported in Table 5.5.1.

5.5.4 *Gaia* and *TESS* phase-folding

Planetary transit detections with *Gaia* have been confirmed, with *Gaia*-1b and *Gaia*-2b being the first such planets (Panahi et al., 2022). Time-series photometry of *Gaia*-7 in the three *Gaia* passbands (G , G_{BP} , and G_{RP}) was retrieved from the *Gaia* archive, as described in Section 5.3. These light curves were cleaned from outliers using a robust sigma-clipping procedure. The resulting datasets were then phase-folded adopting the reference ephemeris listed in Table 5.5.1. The *Gaia* phase-folded photometry was compared with the phase-folded *TESS* light curve, including all available sectors, and its best-fitting transit model (see Section 5.5.2). Figure 5.5.4 shows the combined *TESS* and *Gaia* dataset.

Despite the sparse sampling and low cadence of the *Gaia* observations (46 points in the *Gaia* G band and 45 points in both the G_{BP} and G_{RP} bands), the phase-folded

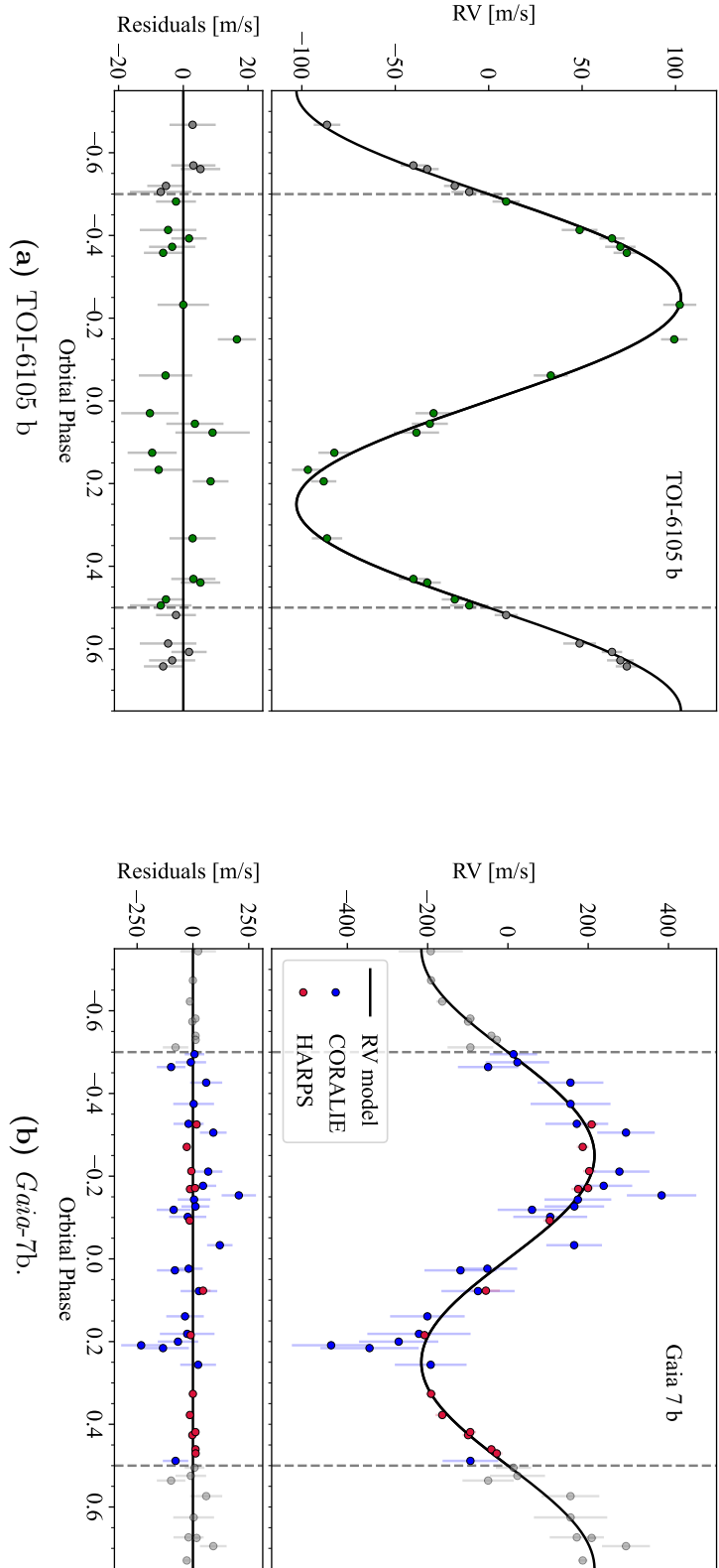


Figure 5.5.3: Radial velocity modeling of TOI-6105 b (left) and Gaia-7b (right) RV planetary signal. *Top panels:* HARPS Phase-folded RV curve (green and blue points for TOI-6105 b and *Gaia*-7b, respectively) and CORALIE data (purple points), together with the transit model (black line). *Bottom panels:* Residuals of the fit.

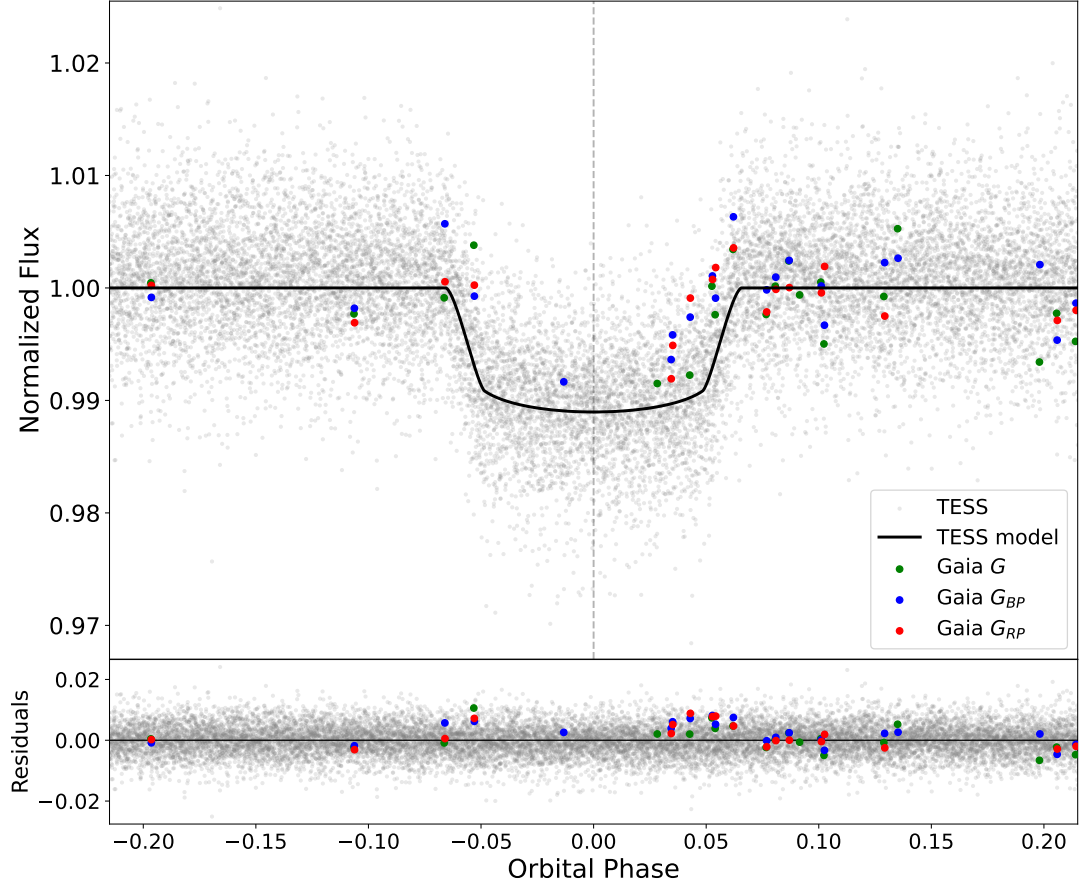


Figure 5.5.4: Photometric comparison of the *Gaia*-7b transit signal using *TESS* and *Gaia* data. Gray dots correspond to the *TESS* observations from all sectors in which *Gaia*-7b was observed. Green, blue, and red points correspond to the *Gaia* G , G_{BP} , and G_{RP} data, respectively. Top panel: normalized phase-folded light curves and the best-fitting transit model (black solid line). Bottom panel: residuals with respect to the transit model.

Gaia measurements are broadly consistent with the transit signal independently detected in the *TESS* photometry. In particular, the G -band data show the clearest agreement with the expected transit phase and depth when compared with the model curve, whereas the G_{BP} and G_{RP} measurements display larger scatter, consistent with their lower photometric precision and reduced number of observations.

5.5.5 Equilibrium temperature, scale height, and transmission spectroscopy metric

To compute the equilibrium temperatures of both TOI-6105 b and *Gaia*-7b, I assumed full day–night heat redistribution and zero Bond albedo, following the same approach described in Chapter 4.5.6. The equilibrium temperature was calculated using Equation 4.5.3. Using the stellar and planetary parameters reported in Tables 5.4.1 and 5.5.1, respectively, and propagating their associated uncertainties, I obtained $T_{\text{eq}} = 1559 \pm 10$ K for TOI-6105 b and $T_{\text{eq}} = 2301 \pm 30$ K for *Gaia*-7b. The latter value is consistent with the classification of *Gaia*-7b as an ultra-hot Jupiter, given its equilibrium temperature above 2000 K.

I then estimated the atmospheric scale height of both targets, assuming an H_2 -dominated, solar-abundance, cloud-free atmosphere, using

$$H = \frac{k_b T_{\text{eq}}}{\mu g}, \quad (5.5.1)$$

where k_b is the Boltzmann constant, $\mu = 2.3 \text{ g mol}^{-1}$ is the mean molecular weight, and g is the planetary surface gravity. The resulting scale heights are $H = 552 \pm 20$ km for TOI-6105 b and $H = 647 \pm 43$ km for *Gaia*-7b.

Furthermore, I estimated the amplitude of spectral features in transmission, δ_λ , using the approximation $\delta_\lambda \sim 4R_p H / R_\star^2$ (Kreidberg, 2018). This resulted in $\delta_\lambda = 318 \pm 14$ ppm for TOI-6105 b and $\delta_\lambda = 218 \pm 21$ ppm for *Gaia*-7b.

Finally, I calculated the transmission spectroscopy metric (TSM) for both planets following Kempton et al. (2018), using the same procedure described in Chapter 4.5.8. I obtained TSM values of 165 ± 8 for TOI-6105 b and 61 ± 6 for *Gaia*-7b. According to the $\text{TSM} > 90$ threshold suggested by Kempton et al. (2018) for giant planets, TOI-6105 b is a promising target for atmospheric characterization, whereas *Gaia*-7b does not reach this threshold. Nevertheless, *Gaia*-7b remains an interesting target because of its ultra-hot Jupiter nature, and three different transmission spectroscopy scenarios can be distinguished from the simulated JWST observations discussed in Section 5.6.4.

5.6 Discussion

5.6.1 Two new hot Jupiters in the First PLATO Field

TOI-6105 b is a HJ planet with an orbital period $P_{\text{orb}} \approx 3.1123$ days, a radius of $R_p = 1.382 \pm 0.012 R_J$ and a mass of $M_p = 0.78 \pm 0.02 M_J$ that orbits a slightly metal-poor star ($[\text{Fe}/\text{H}] = -0.07 \pm 0.01$) with an effective temperature $T_{\text{eff}} = 6133 \pm 23$ K. On the other hand, *Gaia*-7b is an UHJ ($T_{\text{eq}} = 2301 \pm 30$ K) with an orbital period $P_{\text{orb}} \approx 1.5303$ days, a radius of $R_p = 1.72 \pm 0.04 R_J$ and a mass of $M_p = 1.53 \pm 0.07 M_J$, which orbits a metal-rich star ($[\text{Fe}/\text{H}] = 0.24 \pm 0.01$) with an effective temperature $T_{\text{eff}} = 6194 \pm 32$ K. Moreover, *Gaia*-7b is the *seventh* confirmed UHJ currently known in the first PLATO long-pointing field (LOPS2, [Rauer et al., 2025](#); [Nascimbeni et al., 2025](#)), while also having the third best signal (TSM) for atmospheric follow-up observations with JWST, as listed in Table 5.6.1.

These two newly confirmed planets increase the sample of confirmed exoplanets in the LOPS2 field to more than 30 systems. In addition, TOI-6105 b is a favorable target for atmospheric characterization. Its transmission spectroscopy metric value of 165 ± 8 places it 10th among the highest-ranked planets currently known in the field for transmission spectroscopy observations (Table 5.6.1). Among the confirmed planets in LOPS2 with measured masses and $\text{TSM} > 90$ ([Kempton et al., 2018](#)), TOI-6105 b lies within the upper subset of targets, highlighting its suitability for future atmospheric follow-up observations. This makes TOI-6105 b one of the most promising targets for detailed atmospheric characterization in the LOPS2 field and a compelling candidate for observations with facilities such as JWST, as discussed further in Section 5.6.4.

Table 5.6.1: Confirmed HJ planets ($P < 10$ d, $R_p/R_{\oplus} > 8$) in the nominal footprint of the first PLATO field (LOPS2; [Nascimbeni et al. \(2025\)](#)), from the TEPCAT database (retrieved: 2026-07-22). The list is sorted by decreasing TSM, the Transmission Spectroscopy Metric introduced by [Kempton et al. \(2018\)](#), and the horizontal line marks the conventional threshold of high-priority targets for spectroscopic characterization ($\text{TSM} > 90$). The column give: the name of the host star, its effective temperature, the V and 2MASS J magnitudes, the orbital period, the planetary mass and radius in Jupiter units, the TSM metric and a flag to identify the UHJ subsample ($T_{\text{eq}} > 2000$ K.) All the value are taken from TEPCAT with the exception of J (2MASS) and TSM (computed by us).

Name	T_{eff} [K]	V [mag]	J [mag]	P [days]	$M_{\text{p}}/M_{\text{jup}}$	$R_{\text{p}}/R_{\text{jup}}$	T_{eq} [K]	TSM	UHJ?
WASP-101	6440	10.34	9.334	3.586	0.502	1.369	1570	329	
WASP-121	6626	10.52	9.625	1.275	1.17	1.742	2406	307	✓
WASP-062	6230	10.22	9.272	4.412	0.57	1.39	1402	306	
WASP-168	6000	11.85	10.778	4.154	0.42	1.5	1343	304	
WASP-079	6760	10.04	9.299	3.662	0.842	1.625	1785	260	
TOI-640	6460	10.57	9.519	5.004	0.57	1.72	1747	227	
WASP-122	5720	11.0	9.808	1.71	1.284	1.743	1959	194	
WASP-063	5715	11.16	9.818	4.378	0.38	1.43	1575	189	
HATS-43	5099	13.59	12.064	4.389	0.261	1.18	995	186	
TOI-6105 b*	6133	11.30	10.28	3.112	0.78	1.38	1559	165	
WASP-160	5218	13.09	11.591	3.768	0.281	1.093	1100	164	
TOI-622	6400	9.0	8.108	6.405	0.303	0.824	1378	154	
WASP-126	5800	11.2	9.962	3.289	0.28	0.96	1486	150	
TOI-2803	6280	12.53	11.607	1.962	0.975	1.616	1891	128	
TOI-2818	5721	11.92	10.743	4.04	0.71	1.363	1376	117	
NGTS-01	3916	15.52	12.702	2.647	0.812	1.33	791	102	
KELT-15	6003	11.44	10.205	3.329	1.196	1.52	1638	101	
NGTS-06	4730	14.09	12.222	0.882	1.339	1.326	1528	85	
HATS-39	6572	12.75	11.833	4.578	0.63	1.57	1644	84	
WASP-119	5650	12.27	10.924	2.5	1.23	1.4	1565	80	
HATS-51	5758	12.47	11.241	3.349	0.768	1.41	1545	78	
KELT-25	8100	9.84	9.362	4.401	1.8	1.642	2250	73	✓
WASP-023	5046	12.68	10.96	2.944	0.917	1.067	1129	73	
HD_271181	6495	11.47	10.404	4.231	1.22	1.489	1668	70	
WASP-064	5550	12.29	11.368	1.573	1.271	1.271	1690	66	
TOI-2368	5360	12.52	10.916	5.175	0.65	0.967	999	64	
<i>Gaia</i> -7b*	6194	12.77	11.64	1.530	1.53	1.72	2301	61	✓
WASP-159	6000	12.82	11.309	3.84	0.55	1.38	1810	54	
WASP-100	6940	10.8	9.928	2.849	2.03	1.4	2083	53	✓
HATS-44	5080	14.43	12.699	2.744	0.56	1.067	1179	52	
HATS-45	6450	13.31	12.364	4.188	0.7	1.286	1518	45	
NGTS-33	7437	11.46	10.607	2.828	3.63	1.64	1982	43	

NGTS-10	4400	14.34	12.392	0.767	2.162	1.205	1480	41	
TOI-1937	5814	13.24	11.717	0.947	2.01	1.247	2094	40	✓
HATS-55	6095	13.47	12.338	4.204	0.921	1.251	1339	39	
NGTS-23	6057	14.01	13.056	4.076	0.613	1.267	1447	39	
NGTS-31	5710	13.44	12.175	4.163	1.12	1.61	1417	34	
NGTS-03	5600	14.64	13.281	1.675	2.38	1.48	1704	30	
NGTS-17	5650	14.33	13.114	3.243	0.76	1.24	1591	27	
NGTS-15	5600	14.56	13.341	3.276	0.751	1.1	1255	27	
HATS-04	5403	13.46	12.032	2.517	1.323	1.02	1316	25	
WASP-061	6250	12.5	11.219	3.856	2.06	1.22	1555	20	
HATS-42	6060	13.62	12.543	2.292	1.88	1.4	1849	19	
HATS-40	6460	13.38	12.439	3.264	1.59	1.58	2093	17	✓
WASP-120	6450	10.96	10.148	3.611	4.85	1.39	1874	14	
TOI-2184	5966	12.01	10.767	6.907	0.65	1.017	1709	12	
HATS-76	4016	16.68	13.69	1.942	2.629	1.079	939	11	
HATS-66	6500	14.1	13.083	3.141	5.5	1.5	1963	4	
TOI-2416	5808	13.02	11.816	8.275	3.0	0.88	1079	4	
HATS-41	6424	12.68	11.765	4.194	9.7	1.33	1676	3	
HATS-70	7930	12.57	12.139	1.888	12.9	1.384	2749	3	✓

Note. * Planets characterized in this work

Figure 5.6.1 shows the orbital period against the planetary radius of TOI-6105 b and *Gaia*-7b, together with the confirmed planets from both the NASA¹⁰ and TEPcat¹¹ catalogs that are located in the PLATO LOPS2 field.

5.6.2 Radius inflation

From the planetary parameters obtained from the joint photometric and RV analysis detailed in Section 5.5, we assessed whether TOI-6105 b and *Gaia*-7b exhibit inflated radii. As shown in Figure 5.6.2, both planets are more inflated than expected for a pure H/He planet without additional internal heating, given their incident stellar fluxes and the reference model adopted (see, e.g., Thorngren et al., 2016; Thorngren, 2024; Mantovan et al., 2024). One possible explanation

¹⁰<https://exoplanetarchive.ipac.caltech.edu/index.html>

¹¹<https://www.astro.keele.ac.uk/jkt/tepcat/html-catalogue.html>

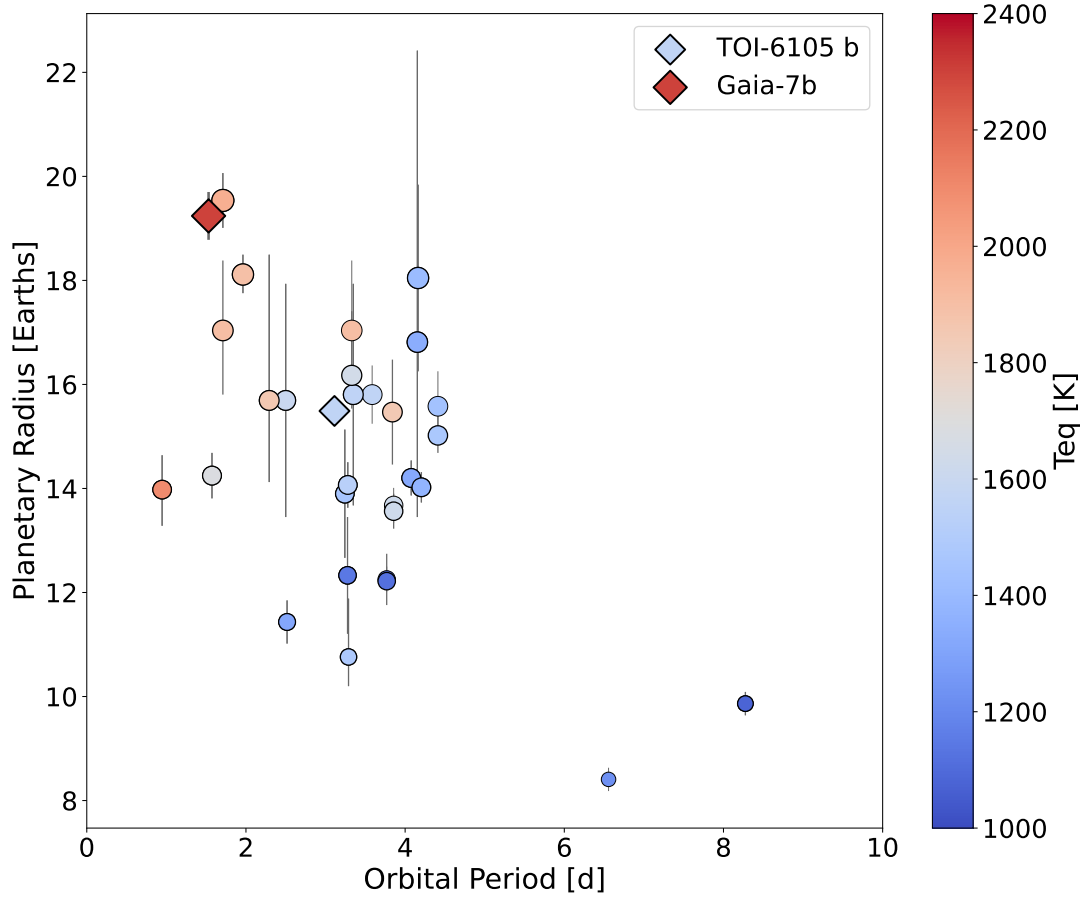


Figure 5.6.1: Orbital period vs planet radius of confirmed planets that are located in the PLATO LOPS2 field. The sizes and colors of each point are relative to their planetary radius and equilibrium temperature. TOI-6105 b and *Gaia*-7b are marked as stars instead of circles.

for this anomalous inflation is the significant incident stellar flux received by both planets (see [Fortney et al., 2021](#), and references therein).

5.6.3 Ephemeris improvement

As described in Chapter 4.5.5, an important step following the analysis of the observational data is the derivation of updated mean ephemerides for both TOI-6105 b and *Gaia*-7b. Improved ephemerides allow future transit times to be predicted with greater precision, which is particularly relevant for planning follow-up observations of transiting exoplanets. For both targets, the updated ephemerides were propagated to 1 January 2030 ($\text{BJD}_{\text{TDB}} = 2462502.5$), following the same procedure and equations (4.5.1) and (4.5.2) described in Chapter 4.5.5.

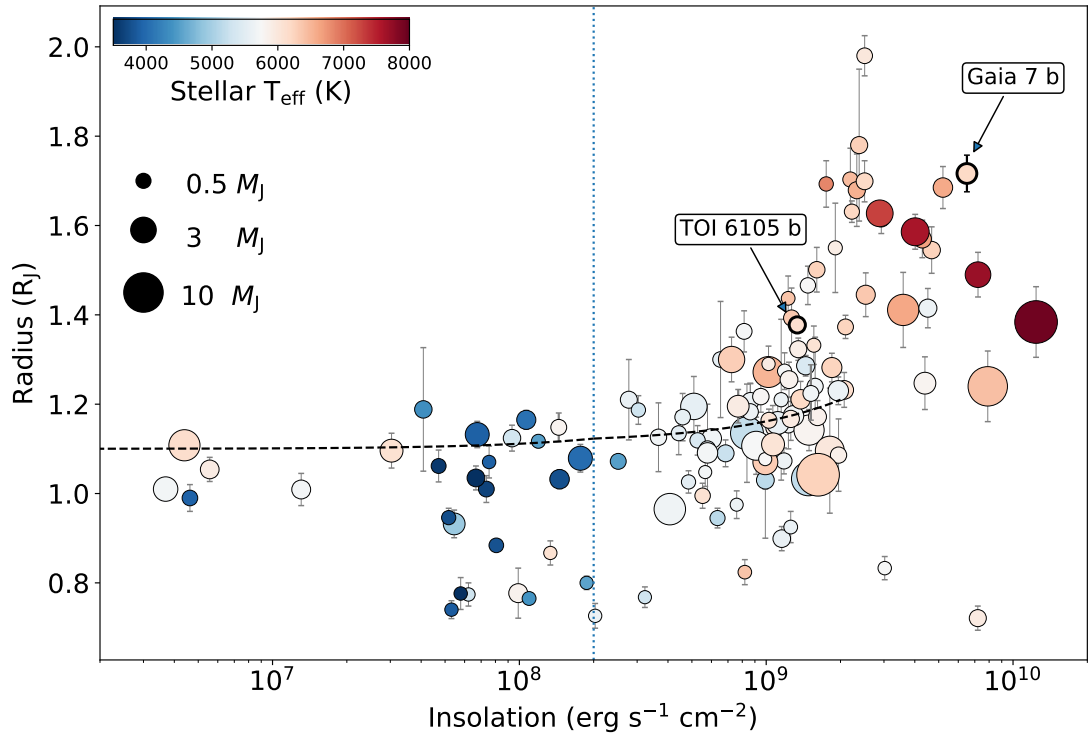


Figure 5.6.2: Incident stellar flux versus planet radius. We colour-code the stellar effective temperature, while the dot size reflects the planetary mass. A pure H/He planet (no metals), 4.5 Gyr old, $1 M_J$, without additional internal heating, is represented by the black dashed line (adapted from [Thorngren, 2024](#)). The inflation threshold of $2 \times 10^8 \text{ erg s}^{-1} \text{cm}^{-2}$ is shown as a vertical line ([Demory and Seager, 2011](#); [Thorngren et al., 2016](#)).

For TOI-6105 b, the uncertainty in the predicted transit time was reduced from approximately 39 minutes to 0.3761 minutes, corresponding to an improvement of 99.03%. For *Gaia*-7b, the uncertainty was reduced to 1.1747 minutes, corresponding to a 53.47% decrease from the previous value of approximately 2.5251 minutes. These results provide substantially more precise transit-time predictions for future observations of both systems.

5.6.4 Prospects for atmospheric characterization

To assess the potential of future observations with JWST to distinguish between different atmospheric scenarios for TOI-6105 b and *Gaia*-7b, illustrative transmission spectra were computed using the TauREx3 retrieval and radiative-transfer framework (Al-Refaie et al., 2021). The resulting spectra were then converted into synthetic *JWST* observations with PandExo (Batalha et al., 2017b), adopting the following configuration: NIRSpec Bright Object Time Series, G140M/F070LP ($R \simeq 1000$), S1600A1 aperture, SUB2048 subarray, optimized groups per integration, an 80% full-well saturation limit, and a constant minimum noise floor of 30 ppm.

Three deliberately simplified atmospheric scenarios were considered as representative bracketing cases, as summarized in Table 5.6.2: (1) a clear atmosphere with relatively high molecular opacity; (2) a clear atmosphere with lower molecular opacity; and (3) an aerosol-dominated limiting case, with the molecular abundances effectively set to negligible values. All models assume an H_2/He -dominated atmosphere, an isothermal temperature profile, Rayleigh scattering, and $\text{H}_2\text{--H}_2/\text{H}_2\text{--He}$ collision-induced absorption. The adopted atmospheric temperatures were 1559.36 K for TOI-6105 b and 2318.92 K for *Gaia*-7b. These scenarios are not intended as predictions of the actual atmospheric compositions of the two planets, but rather as illustrative cases to assess whether different transmission signatures could be distinguished under the adopted observational setup.

The simulated wavelength ranges are approximately 0.82–1.27 μm for TOI-6105 b and 0.70–1.27 μm for *Gaia*-7 b. With the adopted instrumental configuration and noise assumptions, the three scenarios can be distinguished in the simulations (Figure 5.6.3). However, this result should be presented as an idealized model-discrimination exercise rather than as a guaranteed JWST detection, since real

observations may be affected by additional instrumental systematics, stellar contamination, and more complex cloud or atmospheric structures.

The simulations are consistent with the TSM-based ranking presented in Section 5.6.1. TOI-6105 b remains the more favorable transmission-spectroscopy target, with a TSM of 165 ± 8 and an expected transmission feature amplitude of 318 ± 14 ppm, compared with a TSM of 61 ± 6 and an expected amplitude of 218 ± 21 ppm for *Gaia*-7b (Kempton et al., 2018). NIRSpec/G140M therefore provides a suitable configuration for an initial investigation of whether TOI-6105 b possesses a relatively clear, low-mean-molecular-weight atmosphere. Although *Gaia*-7b is expected to be less favorable for transmission spectroscopy, the simulations indicate that the adopted atmospheric scenarios remain distinguishable under the assumed conditions. The main limitations of this assessment are the assumed 30 ppm noise floor, the idealized one-dimensional isothermal atmospheric structure, and the simplified grey-cloud prescription. More complex cloud properties, stellar contamination, and time-correlated instrumental systematics could reduce the discriminating power of real observations.

5.7 Conclusions

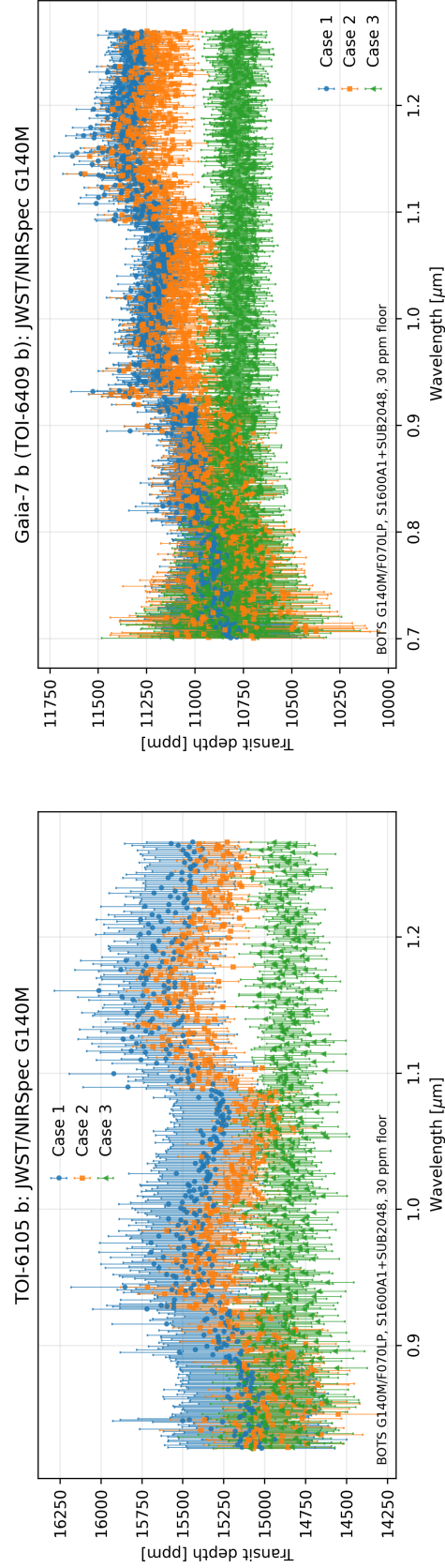
This work presents the confirmation of an HJ (TOI-6105 b) and a UHJ (*Gaia*-7b), both located in the first PLATO field (LOPS2) and consistent with circular orbits. Using HARPS+CORALIE radial-velocity time series together with *TESS* and ground-based photometric observations, we determined the planetary masses and confirmed the planetary nature of both systems.

Precise physical parameters were obtained for TOI-6105 b and *Gaia*-7b. Both planets have radii comparable to, or larger than, Jupiter, with $R_p = 1.382 \pm 0.012 R_{\text{Jup}}$ for TOI-6105 b and $R_p = 1.716 \pm 0.041 R_{\text{Jup}}$ for *Gaia*-7b, and masses of $M_p = 0.783 \pm 0.025 M_{\text{Jup}}$ and $M_p = 1.528 \pm 0.069 M_{\text{Jup}}$, respectively. The derived planetary parameters place both planets above the expected radius of a baseline pure H/He planet without additional internal heating, indicating that they exhibit inflated radii. In addition, the updated orbital ephemerides substantially improve the predicted transit-time precision toward 2030, reducing the uncertainty to approximately 0.38 minutes for TOI-6105 b and 1.17 minutes for *Gaia*-7b.

The atmospheric characterization prospects of both planets were also investigated.

Table 5.6.2: Atmospheric scenarios used in the TauREx simulations. All cases use an H_2/He background, with the TauREx fill-gas ratio parameter fixed to 0.25884514, an isothermal profile, 120 atmospheric layers, Rayleigh scattering, and $\text{H}_2\text{--He}/\text{H}_2\text{--H}_2$ CIA. The equilibrium temperatures are 1559.36 K for TOI-6105 b and 2318.92 K for *Gaia*-7b.

Case	Physical meaning	H_2O	CO_2	CO	CH_4	NH_3	Cloud
Case 1	Clear, high molecular opacity	3.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	5.0×10^{-4}	1.0×10^{-4}	none
Case 2	Clear, lower molecular opacity	7.75×10^{-4}	3.16×10^{-4}	2.83×10^{-4}	7.07×10^{-5}	1.41×10^{-5}	none
Case 3	Aerosol-muted limit	1.0×10^{-12}	1.0×10^{-12}	1.0×10^{-12}	1.0×10^{-12}	1.0×10^{-12}	100 mbar



(a) TOI-6105 b

(b) *Gaia*-7b.

Figure 5.6.3: Synthetic *JWST*/NIRSpec G140M transmission spectra for the three atmospheric cases in Table 5.6.2. The TOI-6105 b simulation covers 0.82–1.27 μm , while the *Gaia*-7b simulation covers 0.70–1.27 μm .

TOI-6105 b, with a TSM of 165 ± 8 , is a particularly favorable target for transmission spectroscopy, whereas *Gaia*-7b has a lower TSM of 61 ± 6 . Exploratory JWST simulations indicate that transmission spectroscopy observations could provide useful constraints on the atmospheric scenarios considered here; however, these simulations are based on idealized atmospheric and instrumental assumptions and should therefore be regarded as a demonstration of potential detectability rather than as physical predictions of the atmospheres of either planet.

The high equilibrium temperature of *Gaia*-7b ($T_{\text{eq}} = 2301 \pm 30$ K) confirms its classification as an UHJ. It is currently the seventh confirmed UHJ known in the first PLATO long-pointing field. The confirmation and characterization of both planets in LOPS2 therefore add two well-characterized giant planets to the population available for future PLATO studies.

Coupled with its nearly continuous two-year coverage, PLATO is expected to provide high-precision photometric observations capable of constraining key properties and mechanisms of UHJs, including tidal deformation and the redistribution of thermal energy (Singh, 2021; Akinsanmi et al., 2024).

Chapter 6

Conclusions

6.1 Main Scientific Contributions

This thesis focused on the physical characterization of three irradiated giant exoplanets through complementary observational techniques, combining transit photometry, radial velocity measurements, and transmission spectroscopy. Rather than focusing on the discovery of new planetary systems, this work aimed to improve our understanding of the physical properties, atmospheric characteristics, and evolutionary processes governing close-in giant planets. Although centered on three individual systems, the results presented here contribute to the broader observational picture of irradiated giant planets and provide useful constraints for future comparative studies.

The principal scientific contributions of this thesis can be summarized as follows:

- The first optical atmospheric characterization of the hot Jupiter TOI-1019 b was presented, providing the first observational constraints on the atmospheric properties of this system (Chapter 4).
- Accurate physical and orbital parameters were determined for the hot Jupiters TOI-6105 b and Gaia-7 b by combining TESS and complementary ground-based photometry with HARPS and CORALIE radial velocity observations, improving the physical characterization of both planetary systems (Chapter 5).
- Together, the results obtained for these three systems expand the sample of

well-characterized irradiated giant planets and provide new observational constraints for studies of atmospheric physics, planetary evolution, and giant planet populations.

Together, these results demonstrate the importance of combining complementary observational techniques to achieve a comprehensive physical characterization of irradiated giant planets. Transit photometry constrains planetary radii and orbital geometry, radial velocity observations determine planetary masses and bulk densities, while transmission spectroscopy probes atmospheric composition and structure. The synergy between these techniques constitutes one of the central themes of this thesis and provides a robust framework for investigating the origin and evolution of close-in giant planets.

6.2 Atmospheric Characterization of TOI-1019 b

The optical transmission spectrum obtained for the hot Jupiter TOI-1019 b provides the first observational constraints on its atmosphere and demonstrates the potential of ground-based transmission spectroscopy for characterizing highly irradiated giant planets. The measured spectrum is consistent with enhanced scattering toward blue optical wavelengths, while no strong alkali absorption features are detected at the precision of the present observations.

The atmospheric retrieval analysis shows that the available data do not uniquely constrain the atmospheric composition of TOI-1019 b. Several atmospheric scenarios remain compatible with the observations, illustrating the degeneracies that can arise when interpreting optical transmission spectra with limited wavelength coverage and observational precision. In particular, the uncertainty in the planetary mass remains an important limitation for the interpretation of the atmospheric signal and for assessing the expected atmospheric scale height.

Despite these limitations, the observations establish a useful observational baseline for future studies of TOI-1019 b. Its inflated radius and favorable atmospheric scale height make it a promising target for additional observations covering broader wavelength ranges and achieving higher precision. Such observations would help distinguish between the atmospheric scenarios that remain consistent with the current spectrum and provide stronger constraints on the physical processes shaping its atmosphere.

More broadly, the results for TOI-1019 b demonstrate that atmospheric characterization of irradiated giant planets requires the combination of sufficiently precise atmospheric observations with accurate knowledge of the underlying planetary properties. The case of TOI-1019 b therefore illustrates the importance of improving both atmospheric and bulk-planet measurements when interpreting transmission spectra and assessing the physical diversity of hot Jupiter atmospheres.

6.3 Physical Characterization of TOI-6105 b and Gaia-7 b

The combined analysis of transit photometry and radial velocity observations provided a precise physical and orbital characterization of the hot Jupiters TOI-6105 b and *Gaia*-7b. The resulting planetary masses and radii, $M_p = 0.783 \pm 0.025 M_{\text{Jup}}$ and $R_p = 1.382 \pm 0.012 R_{\text{Jup}}$ for TOI-6105 b, and $M_p = 1.528 \pm 0.069 M_{\text{Jup}}$ and $R_p = 1.716 \pm 0.041 R_{\text{Jup}}$ for *Gaia*-7b, yield low planetary densities and confirm that both systems are substantially inflated relative to Jupiter.

The characterization of these two planets also highlights the importance of precise bulk properties when interpreting highly irradiated giant planets. Their measured masses and radii provide constraints on their gravitational and structural properties that cannot be obtained from transit photometry alone, while the combination of space- and ground-based photometry with high-precision radial velocities reduces the uncertainties in the parameters relevant for subsequent atmospheric and evolutionary studies.

The improved orbital solutions also allowed the future transit times to be predicted with substantially greater precision. In particular, propagating the updated ephemerides to 1 January 2030 reduced the expected timing uncertainty to approximately 0.38 minutes for TOI-6105 b and 1.17 minutes for *Gaia*-7b. This improvement is relevant for planning future transit observations, for which accurate ephemerides are essential to ensure efficient use of observing time.

The two planets nevertheless differ in their prospects for transmission spectroscopy. TOI-6105 b has a higher Transmission Spectroscopy Metric, $TSM = 165 \pm 8$, than *Gaia*-7b, for which $TSM = 61 \pm 6$, making TOI-6105 b the more favorable target

for transmission spectroscopy. The exploratory JWST simulations presented in Chapter 5 are consistent with this ranking under the adopted idealized assumptions, but should be regarded as an assessment of potential observational discrimination rather than as a prediction of the actual atmospheric properties of either planet.

Together, the results for TOI-6105 b and *Gaia*-7b demonstrate how precise measurements of planetary bulk properties, orbital ephemerides, and atmospheric observability can be combined to establish well-characterized benchmark systems within the PLATO LOPS2 field. Their different equilibrium temperatures and atmospheric prospects further provide a useful basis for comparative studies of the physical processes governing highly irradiated giant planets.

6.4 Implications for Irradiated Giant Planet Physics

The three planets studied in this thesis illustrate complementary aspects of the physical and atmospheric characterization of irradiated giant planets. Although they cannot by themselves establish population-level trends, their combined properties provide a useful comparison of how planetary inflation, irradiation, surface gravity, and observational accessibility affect the interpretation of close-in giant planets.

All three systems exhibit large planetary radii, with TOI-1019 b, TOI-6105 b, and *Gaia*-7b having radii of approximately 2.09, 1.38, and 1.72 R_{Jup} , respectively. The latter two planets also have precisely measured masses, resulting in low bulk densities of approximately 0.39 and 0.40 g cm^{-3} for TOI-6105 b and *Gaia*-7b, respectively. These properties place both planets among the low-density, highly irradiated giant planets for which radius inflation is an important aspect of their physical interpretation. Precise measurements of the planetary radius are particularly important in this context, as they directly affect the derived density and other physical parameters used to investigate the structure and inflation of hot giant planets (Alexoudi, 2022). The results are therefore consistent with the broader picture in which strong stellar irradiation is associated with anomalously large radii in hot Jupiters, while also illustrating that the physical origin and magnitude of the inflation cannot be inferred from irradiation alone (Fortney et al., 2021).

The comparison also highlights the role of planetary gravity in determining the accessibility of their atmospheres. TOI-6105 b and *Gaia*-7b have surface gravities of approximately 10.2 and 12.9 m, s^{-2} , respectively, while their high equilibrium temperatures provide substantial atmospheric scale heights. Consequently, their atmospheric signals are influenced by the combined effect of irradiation, planetary radius, and surface gravity rather than by temperature alone. This provides a physical basis for the different transmission-spectroscopy prospects obtained from the TSM analysis, with TOI-6105 b being the more favorable target despite both planets being highly inflated.

TOI-1019 b provides a complementary case in which the large planetary radius makes the atmosphere potentially accessible to transmission spectroscopy, but the interpretation of the observed optical spectrum remains limited by the available precision, wavelength coverage, and uncertainty in the planetary bulk properties. The comparison with TOI-6105 b and *Gaia*-7b therefore emphasizes that a favorable atmospheric scale height is not sufficient by itself to obtain an unambiguous atmospheric characterization. Accurate planetary masses and radii are required to interpret the atmospheric signal and to distinguish between competing atmospheric scenarios.

The three systems also span a range of irradiation regimes relevant to the atmospheric physics of giant planets. TOI-6105 b has an equilibrium temperature of approximately 1560 K, while *Gaia*-7b reaches approximately 2300 K and therefore lies in the ultrahot-Jupiter regime. TOI-1019 b provides an additional highly irradiated system with a substantially inflated radius. This range makes the three planets useful comparative benchmarks for investigating how increasing irradiation may affect atmospheric structure, chemical composition, scattering processes, and the mechanisms responsible for maintaining inflated planetary radii. However, distinguishing these effects observationally will require broader wavelength coverage and higher-precision atmospheric measurements, since clouds, aerosols, stellar contamination, and instrumental systematics can introduce significant degeneracies in transmission spectra. (Heng and Showman, 2015; Fortney et al., 2021)

Taken together, the results demonstrate that the physical and atmospheric characterization of irradiated giant planets is intrinsically interconnected. Precise masses and radii constrain the planetary gravity and structure, while equilibrium

temperature and stellar irradiation determine the thermal environment in which the atmosphere evolves. Conversely, atmospheric observations provide information on the processes operating in the outer layers of these planets. The three systems studied in this thesis therefore illustrate the need for a combined observational approach in which transit photometry, radial velocities, and transmission spectroscopy are used together to establish physically interpretable benchmark systems.

6.5 Future Prospects

The results presented in this thesis provide several opportunities for future studies of irradiated giant exoplanets. In particular, the characterization of TOI-1019 b, TOI-6105 b, and *Gaia*-7b establishes these systems as promising benchmarks for complementary photometric, spectroscopic, and radial-velocity observations.

Future observations with JWST could extend the atmospheric characterization of these planets to longer wavelengths. TOI-6105 b is particularly favorable for transmission spectroscopy, while *Gaia*-7b provides an interesting target for studying atmospheric processes in the ultrahot-Jupiter regime. Additional observations of TOI-1019 b at infrared wavelengths would likewise help to complement the optical transmission spectrum presented in this thesis.

The expected long-duration monitoring of the LOPS2 field by PLATO will provide further opportunities to refine transit ephemerides and planetary parameters, as well as to investigate long-term photometric variability and, potentially, phase-dependent signals in highly irradiated planets (Nascimbeni et al., 2025; Singh, 2021; Akinsanmi et al., 2024).

Finally, combining PLATO observations with existing TESS, ground-based, radial-velocity, and atmospheric observations will enable more homogeneous comparative studies of the irradiated giant planets within LOPS2. Such studies could help investigate the connections between planetary inflation, irradiation, atmospheric properties, and the dynamical evolution of these systems.

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Appendix A

A1 *TESS* light-curve masking example

The following example code shows the parameters that are required to perform the normalization and masking of the *TESS* PDCSAP light-curves of TOI-1019, Sector 34, using *wotan*. This can be applied to any TESS light curve by adjusting the respective file name, T_0 , orbital period, and transit duration of the studied TOI.

```

1 from astropy.io import fits
2 from astropy.table import Table, QTable, Column, MaskedColumn
3 from astropy.timeseries import TimeSeries
4 import numpy as np
5 import astropy.units as u
6 import matplotlib.pyplot as plt
7 from astropy.timeseries import LombScargle
8 from wotan import flatten
9 from wotan import transit_mask
10
11 #First, the respective TESS light curve table from one of the target
    's sector is loaded
12
13 ts = Table.read('tess2021014023720-s0034-0000000341420329-0204-s_lc.
    fits', unit_parse_strict='silent', format='fits')
14
15 #The light curve file's respective columns are read and the TESS
    planetary parameters are established.
16
17 time= ts['TIME']
18 flux= ts['PDCSAP_FLUX']
19

```

```

20 T0 = 2232.4457985663266
21 period = 5.2341007583314
22 transit= 0.154492247290962503_#Transt in days
23
24 #The flatten functions from the packages are determined, with the 3-
    transit window established.
25
26 flatten_lc, trend_lc = flatten(time, flux, window_length=3*transit,
    return_trend=True, method='biweight')
27
28 #The mask is created
29
30 mask = transit_mask(time=time, period= period, duration= transit,
    T0=T0)
31
32
33 Corr_Flat, Corr_Trend = flatten(time, flux, window_length=3*transit
    , return_trend=True, method='biweight', mask = mask)
34
35
36 #Finally the different plots for the original light curve, the mask,
    and the light curve with the masking are created and shown.
37
38 plt.plot(time[~mask], flux[~mask], marker='.', color='gray',
    markersize=1, linewidth=0)
39 plt.plot(time, trend_lc, linewidth=2, color='red')
40 plt.plot(time, Corr_Trend, linewidth=2, color='lime', linestyle='—'
    )
41 plt.plot(time[mask], flux[mask], 'm.', markersize=1, label='Transit
    Mask')
42 plt.xlabel('BJD')
43 plt.ylabel('PDCSAP Flux (e-/s)')
44 plt.show()

```

A2 PyLDTk codes

This section provides the example codes of the PyLDTk package used in this thesis.

A2.1 Limb-darkening for *TESS* filters

Example code to determine the quadratic limb-darkening (LD) coefficients, u_1 and u_2 , and their uncertainties, of TOI-1019 for TESS filters.

```

1 import numpy as np
2 import matplotlib.pyplot as plt
3 from ldtk import SVOFilter, LDPSetCreator, TabulatedFilter
4 from IPython.display import display, Latex
5 import pandas as pd
6 from ldtk import BoxcarFilter
7
8 def create_cheops():
9     df = pd.read_csv("CHEOPS_bandpass.csv", header=0, names=[ '
10         wavelength', 'qe', 'throughput', 'passband' ])
11     return TabulatedFilter('CHEOPS', df.wavelength.values, df.
12         passband.values)
13
14 tess_f = SVOFilter('TESS')
15 filters = [tess_f]
16
17 sc = LDPSetCreator(teff=(6900,97), logg=(4.167,0.016), z=(-0.0114,
18     0.088), filters=filters)
19
20 ps = sc.create_profiles(nsamples=2000)
21 ps.resample_linear_z(100)
22
23 ps.set_uncertainty_multiplier(10)
24
25 qm, qe = ps.coeffs_qd(do_mc=True, n_mc_samples=10000)
26
27 for i, (c, e) in enumerate(zip(qm, qe)):
28     display(Latex('Filter {n} $\quad u_{i:d} = {c[0]:5.4f} \pm {e
29         [0]:5.4f} \quad$'
30         'v_{i:d} = {c[1]:5.4f} \pm {e[1]:5.4f}$'.format(n
31             =filters[i].name, i=i+1, c=c, e=e)))
32
33 print(qm)
34 print(qe)

```

A2.2 Limb-darkening for IMACS filters

Example code to determine the quadratic limb-darkening (LD) coefficients, u_1 and u_2 , and their uncertainties, of TOI-1019 for the Magellan-Baade telescope filters for all 13 spectral channels.

```

1 import numpy as np
2 import matplotlib.pyplot as plt
3 from ldtk import SVOFilter, LDPSetCreator, TabulatedFilter
4 from IPython.display import display, Latex
5 import pandas as pd
6 from ldtk import BoxcarFilter
7
8 def create_cheops():
9     df = pd.read_csv("CHEOPS_bandpass.csv", header=0, names=[
10         'wavelength', 'qe', 'throughput', 'passband'])
11     return TabulatedFilter('CHEOPS', df.wavelength.values, df.
12         passband.values)
13
14 filter_magellan1 = BoxcarFilter('baade1', 370.0, 400.0)
15 filter_magellan2 = BoxcarFilter('baade2', 416.0, 440.0)
16 filter_magellan3 = BoxcarFilter('baade3', 440.0, 460.0)
17 filter_magellan4 = BoxcarFilter('baade4', 467.5, 482.5)
18 filter_magellan5 = BoxcarFilter('baade5', 482.5, 497.5)
19 filter_magellan6 = BoxcarFilter('baade6', 511.5, 541.5)
20 filter_magellan7 = BoxcarFilter('baade7', 541.1, 570.0)
21 filter_magellan8 = BoxcarFilter('baade8', 577.5, 597.0)
22 filter_magellan9 = BoxcarFilter('baade9', 597.0, 616.5)
23 filter_magellan10 = BoxcarFilter('baade10', 623.0, 639.9)
24 filter_magellan11 = BoxcarFilter('baade11', 639.9, 657.0)
25 filter_magellan12 = BoxcarFilter('baade12', 668.5, 683.0)
26 filter_magellan13 = BoxcarFilter('baade13', 694.0, 716.5)
27
28 filters = [filter_magellan1,
29 filter_magellan2,
30 filter_magellan3,
31 filter_magellan4,
32 filter_magellan5,
33 filter_magellan6,
34 filter_magellan7,
35 filter_magellan8,
36 filter_magellan9,

```

```

35 filter_magellan10 ,
36 filter_magellan11 ,
37 filter_magellan12 ,
38 filter_magellan13 ,
39 filter_magellan14 ]
40
41 sc = LDPSetCreator( teff=(6900,97) , logg=(4.167,0.016) , z=(-0.0114,
    0.088) , filters=filters )
42
43 ps = sc.create_profiles( nsamples=2000 )
44 ps.resample_linear_z(100)
45
46 ps.set_uncertainty_multiplier(10)
47
48 qm, qe = ps.coeffs_qd( do_mc=True , n_mc_samples=10000 )
49
50 for i, (c, e) in enumerate( zip( qm, qe ) ):
51     display( Latex( 'Filter {n} $\quad$ u$_{i:d}$ = {c[0]:5.4f} $\pm$ {e
        [0]:5.4f} $\quad$ '
52                 'v$_{i:d}$ = {c[1]:5.4f} $\pm$ {e[1]:5.4f}$' .format( n
        =filters[i].name , i=i+1, c=c, e=e ) ) )
53
54 print( 'Values qm: ' )
55 print( qm )
56 print( 'Values qe: ' )
57 print( qe )

```

A2.3 Limb-darkening for TOI-6105 ground-based photometry

Example code to determine the quadratic limb-darkening (LD) coefficients, u_1 and u_2 , and their uncertainties, for TOI-6105 ground-based photometry.

```

1 import numpy as np
2 import matplotlib.pyplot as plt
3 from ldtk import SVOFilter , LDPSetCreator , TabulatedFilter ,
    BoxcarFilter
4 from IPython.display import display , Latex
5 import pandas as pd
6
7 def create_cheops():

```

```

8     df = pd.read_csv("CHEOPS_bandpass.csv", header=0, names=[ '
    wavelength', 'qe', 'throughput', 'passband' ])
9     return TabulatedFilter('CHEOPS', df.wavelength.values, df.
    passband.values)
10
11 # 1. Identify filters using the exact SVO IDs from database
12
13 filter_pest_gp = SVOFilter('SLOAN/SDSS.g')
14 filter_pest_ip = SVOFilter('SLOAN/SDSS.i')
15 filter_hwd_rc = SVOFilter('Generic/Cousins.R')
16
17 # 2. Renaming variables for clean print report
18
19 filter_pest_gp.name = 'PEST gp'
20 filter_pest_ip.name = 'PEST ip'
21 filter_hwd_rc.name = 'Hwd Rc'
22
23 # 3. Group all filters in a single array to make a simultaneous
    processing
24
25 filters = [filter_pest_gp, filter_pest_ip, filter_hwd_rc]
26
27 # 4. Configuring the LDTk creator with the respective stellar
    parameters TOI-6105
28
29 sc = LDPSetCreator(teff=(6133, 23), logg=(4.15, 0.03), z=(-0.07,
    0.01), filters=filters)
30
31 # 5. Creating the profiles
32
33 ps = sc.create_profiles(nsamples=2000)
34 ps.resample_linear_z(100)
35 ps.set_uncertainty_multiplier(10)
36
37 # 6. Calculating the coefficients qm and qe
38
39 qm, qe = ps.coeffs_qd(do_mc=True, n_mc_samples=10000)
40
41 # 7. Printing the results for each filter
42 print("\n—— RESULTING VALUES FOR EACH TELESCOPE AND FILTER ——")
43 for i in range(len(filters)):
44     filter_name = filters[i].name

```

```

45     print(f"\n[Values for {filter_name}]\n")
46     print(f"  Mean Coefficients (qm): u1 = {qm[i][0]:.4f}, u2 = {qm[
i][1]:.4f}")
47     print(f"  Uncertainties      (qe): e1 = {qe[i][0]:.4f}, e2 = {qe[
i][1]:.4f}")

```

A2.4 Limb-darkening for *Gaia*-7 ground-based photometry

Example code to determine the quadratic limb-darkening (LD) coefficients, u_1 and u_2 , and their uncertainties, for *Gaia*-7 ground-based photometry.

```

1
2 import numpy as np
3 import matplotlib.pyplot as plt
4 from ldtk import SVOFilter, LDPSetCreator, TabulatedFilter,
   BoxcarFilter
5 from IPython.display import display, Latex
6 import pandas as pd
7
8 def create_cheops():
9     df = pd.read_csv("CHEOPS_bandpass.csv", header=0, names=[ '
wavelength', 'qe', 'throughput', 'passband' ])
10     return TabulatedFilter('CHEOPS', df.wavelength.values, df.
passband.values)
11
12 # 1. Identify filters using the exact SVO IDs from database
13
14 filter_SAAO_gp = SVOFilter('SLOAN/SDSS.g')
15 filter_hwd_gp = SVOFilter('SLOAN/SDSS.g')
16
17 # 2. Renaming variables for clean print report
18
19 filter_SAAO_gp.name = 'SAAO gp'
20 filter_hwd_gp.name = 'Hwd gc'
21
22 # 3. Group all filters in a single array to make a simultaneous
   processing
23
24 filters = [filter_SAAO_gp, filter_hwd_gp]
25
26 # 4. Configuring the LDTk creator with the respective stellar
   parameters Gaia-7

```

```

27
28 sc = LDPSetCreator(teff=(6194,32), logg=(4.01,0.03), z=(0.24, 0.01),
    filters=filters)
29
30 # 5. Creating the profiles
31
32 ps = sc.create_profiles(nsamples=2000)
33 ps.resample_linear_z(100)
34 ps.set_uncertainty_multiplier(10)
35
36 # 6. Calculating the coefficients qm and qe
37
38 qm, qe = ps.coefs_qd(do_mc=True, n_mc_samples=10000)
39
40 # 7. Printing the results for each filter
41 print("\n—— RESULTING VALUES FOR EACH TELESCOPE AND FILTER ——")
42 for i in range(len(filters)):
43     filter_name = filters[i].name
44     print(f"\n[Values for {filter_name}]")
45     print(f"  Mean Coefficients (qm): u1 = {qm[i][0]:}, u2 = {qm[i][1]:}")
46     print(f"  Uncertainties      (qe): e1 = {qe[i][0]:}, e2 = {qe[i][1]:}")

```

A3 PyORBIT file configuration

A3.1 TOI-1019's yaml file structure for *TESS* photometry analysis

```

1 inputs:
2   LCdata_TESS_Sec34:
3     file: PyORB_Dat_Sec34_Test.dat
4     kind: Phot
5     models:
6       - lc_model_TESS_SPOC
7       - jitter_TESS_s34
8
9   LCdata_TESS_Sec35:
10    file: PyORB_Dat_Sec35_Test.dat
11    kind: Phot

```

```
12     models:
13         - lc_model_TESS_SPOC
14         - jitter_TESS_s35
15
16 LCdata_TESS_Sec36:
17     file: PyORB_Dat_Sec36_Test.dat
18     kind: Phot
19     models:
20         - lc_model_TESS_SPOC
21         - jitter_TESS_s36
22
23 LCdata_TESS_Sec61:
24     file: PyORB_Dat_Sec61_Test.dat
25     kind: Phot
26     models:
27         - lc_model_TESS_SPOC
28         - jitter_TESS_s61
29
30 LCdata_TESS_Sec62:
31     file: PyORB_Dat_Sec62_Test.dat
32     kind: Phot
33     models:
34         - lc_model_TESS_SPOC
35         - jitter_TESS_s62
36
37 LCdata_TESS_Sec63:
38     file: PyORB_Dat_Sec63_Test.dat
39     kind: Phot
40     models:
41         - lc_model_TESS_SPOC
42         - jitter_TESS_s63
43
44 LCdata_TESS_Sec88:
45     file: PyORB_Dat_Sec88_Test.dat
46     kind: Phot
47     models:
48         - lc_model_TESS_SPOC
49         - jitter_TESS_s88
50
51 LCdata_TESS_Sec89:
52     file: PyORB_Dat_Sec89_Test.dat
53     kind: Phot
```

```
54     models:
55         - lc_model_TESS_SPOC
56         - jitter_TESS_s89
57
58 LCdata_TESS_Sec90:
59     file: PyORB_Dat_Sec90_Test.dat
60     kind: Phot
61     models:
62         - lc_model_TESS_SPOC
63         - jitter_TESS_s90
64
65 common:
66     planets:
67         b:
68             orbit: circular
69             parametrization: Eastman2013_Tcent
70             boundaries:
71                 Tc: [2231, 2233]
72                 P: [5.22, 5.24]
73                 b: [0,1]
74
75     star:
76         star_parameters:
77             priors:
78                 radius: ['Gaussian', 1.62423, 0.016]
79                 mass: ['Gaussian', 1.435, 0.047]
80                 density: ['Gaussian', 0.335, 0.016]
81             boundaries:
82                 density: [0.1, 1.0]
83     limb_darkening_TESS:
84         type: ld_quadratic
85         parametrization: Kipping
86         priors:
87             ld_c1: ['Gaussian', 0.34742916, 0.10805666]
88             ld_c2: ['Gaussian', 0.13636816, 0.12471228]
89
90
91 jitter_TESS_s34:
92     type: common_jitter
93 jitter_TESS_s35:
94     type: common_jitter
95 jitter_TESS_s36:
```

```
96     type: common_jitter
97 jitter_TESS_s61:
98     type: common_jitter
99 jitter_TESS_s62:
100    type: common_jitter
101 jitter_TESS_s63:
102    type: common_jitter
103 jitter_TESS_s88:
104    type: common_jitter
105 jitter_TESS_s89:
106    type: common_jitter
107 jitter_TESS_s90:
108    type: common_jitter
109
110 models:
111   lc_model_TESS_SPOC:
112     kind: batman_transit
113     planets:
114       - b
115     limb_darkening: limb_darkening_TESS
116     supersample_factor: 1
117     exposure_time: 120.00
118
119 parameters:
120   Tref: 2232
121   use_tex: False
122 solver:
123   pyde:
124     ngen: 100000
125     npop_mult: 4
126
127   emcee:
128     npop_mult: 4
129     nsteps: 100000
130     nburn: 25000
131     nsave: 5000
132     thin: 200
133
134   nested_sampling:
135     nlive: 1000
136     num_repeats_mult: 5
137     sampling_efficiency: 0.30
```

```
138 | recenter_bounds: True
```

A3.2 TOI-6105's yaml file structure for photometric and radial velocity analysis

```
1 inputs:
2   LCdata_TESS_Sec07:
3     file: PyORB_Dat_Sec07_Test.dat
4     kind: Phot
5     models:
6       - lc_model_TESS_SPOC1
7       - jitter_TESS_s07
8
9   LCdata_TESS_Sec08:
10    file: PyORB_Dat_Sec08_Test.dat
11    kind: Phot
12    models:
13      - lc_model_TESS_SPOC1
14      - jitter_TESS_s08
15
16  LCdata_TESS_Sec34:
17    file: PyORB_Dat_Sec34_Test.dat
18    kind: Phot
19    models:
20      - lc_model_TESS_SPOC2
21      - jitter_TESS_s34
22
23  LCdata_TESS_Sec35:
24    file: PyORB_Dat_Sec35_Test.dat
25    kind: Phot
26    models:
27      - lc_model_TESS_SPOC2
28      - jitter_TESS_s35
29
30  LCdata_TESS_Sec61:
31    file: PyORB_Dat_Sec61_Test.dat
32    kind: Phot
33    models:
34      - lc_model_TESS
35      - jitter_TESS_s61
36
```

```

37 LCdata_TESS_Sec62:
38   file: PyORB_Dat_Sec62_Test.dat
39   kind: Phot
40   models:
41     - lc_model_TESS
42     - jitter_TESS_s62
43
44 LCdata_TESS_Sec88:
45   file: PyORB_Dat_Sec88_Test.dat
46   kind: Phot
47   models:
48     - lc_model_TESS
49     - jitter_TESS_s88
50
51 LCdata_TESS_Sec89:
52   file: PyORB_Dat_Sec89_Test.dat
53   kind: Phot
54   models:
55     - lc_model_TESS
56     - jitter_TESS_s89
57
58 Ground_Data_1:
59   file: TIC182405015-01_20230403_Hwd_Rc_9px_Measurements_DETREND.
60   dat
61   kind: Phot #Filter Rc
62   models:
63     - lc_model_GB1
64     - jitter_GB1
65
66 Ground_Data_2:
67   file: TIC182405015-01_20240108_PEST_gp_DETREND.dat
68   kind: Phot #Filter gp
69   models:
70     - lc_model_GB2
71     - jitter_GB2
72
73 Ground_Data_3:
74   file: TIC182405015-01_20240108_PEST_ip_DETREND.dat
75   kind: Phot #Filter ip
76   models:
77     - lc_model_GB3
78     - jitter_GB3

```

```
78
79 RVdata:
80     file: RV_HARPS_TOI6105_Mod.dat
81     kind: RV
82     models:
83         - radial_velocities
84
85 common:
86     planets:
87         b:
88             orbit: circular
89             parametrization: Eastman2013_Tcent
90             boundaries:
91                 Tc: [2602, 2606]
92                 P: [3.10, 3.12]
93                 K: [0.01, 2000.0]
94                 b: [0,1]
95             spaces:
96                 K: Linear
97                 P: Linear
98
99     star:
100     star_parameters:
101         priors:
102             radius: ['Gaussian', 1.19, 0.01]
103             mass: ['Gaussian', 1.08, 0.02]
104             density: ['Gaussian', 0.65, 0.01]
105         boundaries:
106             density: [0.5, 2.0]
107     limb_darkening_TESS:
108         type: ld_quadratic
109         parametrization: Kipping
110         priors:
111             ld_c1: ['Gaussian', 0.388, 0.100]
112             ld_c2: ['Gaussian', 0.135, 0.100]
113
114     limb_darkening_Ground1: #Hwd Rc
115         type: ld_quadratic
116         parametrization: Kipping
117         priors:
118             ld_c1: ['Gaussian', 0.4623, 0.100]
119             ld_c2: ['Gaussian', 0.1430, 0.100]
```

```

120
121     limb_darkening_Ground2: #PEST gp
122         type: ld_quadratic
123         parametrization: Kipping
124         priors:
125             ld_c1: [ 'Gaussian ',0.6397, 0.100 ]
126             ld_c2: [ 'Gaussian ',0.1311, 0.100 ]
127
128     limb_darkening_Ground3: #PEST ip
129         type: ld_quadratic
130         parametrization: Kipping
131         priors:
132             ld_c1: [ 'Gaussian ',0.3972, 0.100 ]
133             ld_c2: [ 'Gaussian ',0.1331, 0.100 ]
134
135     jitter_TESS_s07:
136         type: common_jitter
137     jitter_TESS_s08:
138         type: common_jitter
139     jitter_TESS_s34:
140         type: common_jitter
141     jitter_TESS_s35:
142         type: common_jitter
143     jitter_TESS_s61:
144         type: common_jitter
145     jitter_TESS_s62:
146         type: common_jitter
147     jitter_TESS_s88:
148         type: common_jitter
149     jitter_TESS_s89:
150         type: common_jitter
151     jitter_GB1:
152         type: common_jitter
153     jitter_GB2:
154         type: common_jitter
155     jitter_GB3:
156         type: common_jitter
157
158 models:
159     radial_velocities:
160         planets:
161             - b

```

```
162     nthreads: 64
163
164     lc_model_TESS_SPOC1:
165         kind: batman_transit
166         planets:
167             - b
168         limb_darkening: limb_darkening_TESS
169         supersample_factor: 7
170         exposure_time: 1800.00
171
172     lc_model_TESS_SPOC2:
173         kind: batman_transit
174         planets:
175             - b
176         limb_darkening: limb_darkening_TESS
177         supersample_factor: 5
178         exposure_time: 600.00
179
180     lc_model_TESS:
181         kind: batman_transit
182         planets:
183             - b
184         limb_darkening: limb_darkening_TESS
185         supersample_factor: 1
186         exposure_time: 120.00
187
188     lc_model_GB1:
189         kind: batman_transit
190         planets:
191             - b
192         limb_darkening: limb_darkening_Ground1 #Hwd Filter Rc
193         supersample_factor: 1
194         exposure_time: 240.00
195
196     lc_model_GB2:
197         kind: batman_transit
198         planets:
199             - b
200         limb_darkening: limb_darkening_Ground2 #PEST gp
201         supersample_factor: 1
202         exposure_time: 240.00
203
```

```

204 lc_model_GB3:
205     kind: batman_transit
206     planets:
207         - b
208     limb_darkening: limb_darkening_Ground3 #PEST ip
209     supersample_factor: 1
210     exposure_time: 240.00
211
212 parameters:
213     Tref: 1494
214     use_tex: False
215 solver:
216     pyde:
217         ngen: 100000
218         npop_mult: 4
219
220     emcee:
221         npop_mult: 4
222         nsteps: 100000
223         nburn: 25000
224         nsave: 5000
225         thin: 200
226
227     nested_sampling:
228         nlive: 1000
229         num_repeats_mult: 5
230         sampling_efficiency: 0.30
231         shutdown_jitter: False
232     recenter_bounds: True

```

A3.3 *Gaia-7*'s yaml file for photometric and radial velocity analysis

```

1 inputs:
2     LCdata_TESS_Sec07:
3         file: PyORB_Dat_Sec06_Test.dat
4         kind: Phot
5         models:
6             - lc_model_TESS_QLP1
7             - jitter_TESS_s06
8

```

```
9  LCdata_TESS_Sec08:
10     file: PyORB_Dat_Sec07_Test.dat
11     kind: Phot
12     models:
13         - lc_model_TESS_QLP1
14         - jitter_TESS_s07
15
16  LCdata_TESS_Sec33:
17     file: PyORB_Dat_Sec33_Test.dat
18     kind: Phot
19     models:
20         - lc_model_TESS_QLP2
21         - jitter_TESS_s33
22
23  LCdata_TESS_Sec34:
24     file: PyORB_Dat_Sec34_Test.dat
25     kind: Phot
26     models:
27         - lc_model_TESS_QLP2
28         - jitter_TESS_s34
29
30  LCdata_TESS_Sec61:
31     file: PyORB_Dat_Sec61_Test.dat
32     kind: Phot
33     models:
34         - lc_model_TESS_QLP3
35         - jitter_TESS_s61
36
37  LCdata_TESS_Sec87:
38     file: PyORB_Dat_Sec87_Test.dat
39     kind: Phot
40     models:
41         - lc_model_TESS
42         - jitter_TESS_s87
43
44  LCdata_TESS_Sec88:
45     file: PyORB_Dat_Sec88_Test.dat
46     kind: Phot
47     models:
48         - lc_model_TESS
49         - jitter_TESS_s88
50
```

```

51  RVdata:
52      file: RV_HARPS_TOI6409_Mod.dat
53      kind: RV
54      models:
55          - radial_velocities
56
57  RV_CORALIE:
58      file: GAIA_7b_CORALIE_Mod.dat
59      kind: RV
60      models:
61          - radial_velocities
62
63  LCdata_Ground1:
64      file: TIC97279971-01_20231219_Hwd_gp_11px_Measurements_DETREND.
65      dat
66      kind: Phot
67      models:
68          - lc_model_Ground1
69          - jitter_GB1
70
71  LCdata_Ground2:
72      file: TIC97279971-01_20231214_LCO-SAAO-0m35_gp_DETREND.dat
73      kind: Phot
74      models:
75          - lc_model_Ground2
76          - jitter_GB2
77
78  LCdata_Ground3:
79      file: TIC97279971-01_20240204_LCO-SAAO-0m35_gp_DETREND.dat
80      kind: Phot
81      models:
82          - lc_model_Ground2
83          - jitter_GB3
84
85  common:
86      planets:
87          b:
88              orbit: circular
89              parametrization: Eastman2013_Tcent
90              boundaries:
91                  Tc: [ 2579, 2581 ]
92                  P: [ 1.52, 1.54 ]

```

```
192         K: [0.01, 2000.0]
193         b: [0,1]
194     spaces:
195         K: Linear
196         P: Linear
197
198     star:
199         star_parameters:
200             priors:
201                 radius: ['Gaussian', 1.74, 0.04]
202                 mass: ['Gaussian', 1.37, 0.075]
203                 density: ['Gaussian', 0.25, 0.02]
204             boundaries:
205                 density: [0.1, 1.0]
206     limb_darkening_TESS:
207         type: ld_quadratic
208         parametrization: Kipping
209         priors:
210             ld_c1: ['Gaussian', 0.403, 0.100]
211             ld_c2: ['Gaussian', 0.130, 0.101]
212     limb_darkening_Hwdgp:
213         type: ld_quadratic
214         parametrization: Kipping
215         priors:
216             ld_c1: ['Gaussian', 0.4623, 0.100]
217             ld_c2: ['Gaussian', 0.1430, 0.100]
218     limb_darkening_SAAO:
219         type: ld_quadratic
220         parametrization: Kipping
221         priors:
222             ld_c1: ['Gaussian', 0.4623, 0.100]
223             ld_c2: ['Gaussian', 0.1430, 0.100]
224
225     jitter_TESS_s06:
226         type: common_jitter
227     jitter_TESS_s07:
228         type: common_jitter
229     jitter_TESS_s33:
230         type: common_jitter
231     jitter_TESS_s34:
232         type: common_jitter
233     jitter_TESS_s61:
```

```
134     type: common_jitter
135 jitter_TESS_s87:
136     type: common_jitter
137 jitter_TESS_s88:
138     type: common_jitter
139 jitter_GB1:
140     type: common_jitter
141 jitter_GB2:
142     type: common_jitter
143 jitter_GB3:
144     type: common_jitter
145
146 models:
147     radial_velocities:
148         planets:
149             - b
150         nthreads: 64
151
152 lc_model_TESS_QLP1:
153     kind: batman_transit
154     planets:
155         - b
156     limb_darkening: limb_darkening_TESS
157     supersample_factor: 7
158     exposure_time: 1800.00
159
160 lc_model_TESS_QLP2:
161     kind: batman_transit
162     planets:
163         - b
164     limb_darkening: limb_darkening_TESS
165     supersample_factor: 5
166     exposure_time: 600.00
167
168 lc_model_TESS_QLP3:
169     kind: batman_transit
170     planets:
171         - b
172     limb_darkening: limb_darkening_TESS
173     supersample_factor: 3
174     exposure_time: 200.00
175
```

```
176 lc_model_TESS:
177     kind: batman_transit
178     planets:
179         - b
180     limb_darkening: limb_darkening_TESS
181     supersample_factor: 1
182     exposure_time: 120.00
183
184 lc_model_Ground1:
185     kind: batman_transit
186     planets:
187         - b
188     limb_darkening: limb_darkening_Hwdgp
189     supersample_factor: 1
190     exposure_time: 300.00
191
192 lc_model_Ground2:
193     kind: batman_transit
194     planets:
195         - b
196     limb_darkening: limb_darkening_SAAO
197     supersample_factor: 1
198     exposure_time: 110.00
199
200 parameters:
201     Tref: 1468
202     use_tex: False
203 solver:
204     pyde:
205         ngen: 100000
206         npop_mult: 4
207
208     emcee:
209         npop_mult: 4
210         nsteps: 100000
211         nburn: 25000
212         nsave: 5000
213         thin: 200
214
215     nested_sampling:
216         nlive: 1000
217         num_repeats_mult: 5
```

```

218     sampling_efficiency: 0.30
219     shutdown_jitter: False
220     recenter_bounds: True

```

A4 Retrieval experiment for TOI-1019: Additional information

For the atmospheric retrieval experiment, the ExoMol database (Tennyson et al., 2016, 2024) was consulted to identify several atomic and molecular species with significant opacity in the optical regime probed by IMACS. We deemed seven species as having substantial opacity to warrant exploration: Na (e.g., Allard et al., 2019), TiO (e.g., McKemmish et al., 2019), VO (e.g., McKemmish et al., 2024), MgO (e.g., Li et al., 2019), H₂O (e.g., Polyansky et al., 2018), NH₃ (e.g., Coles et al., 2019), NaH (e.g., Rivlin et al., 2015). Although widely explored within the literature as a potential optical absorber, we neglected to include K within our retrieval models, as its most prominent doublet feature lies outside the IMACS wavelength coverage at 0.77 μm . Absorption from Rayleigh scattering and collision-induced absorption (H₂-H₂ and H₂-He pairs) are always considered.

A5 Additional Figures

A5.1 IMACS 1D Spectra Alignment plots

A5.2 Spectral channel plot

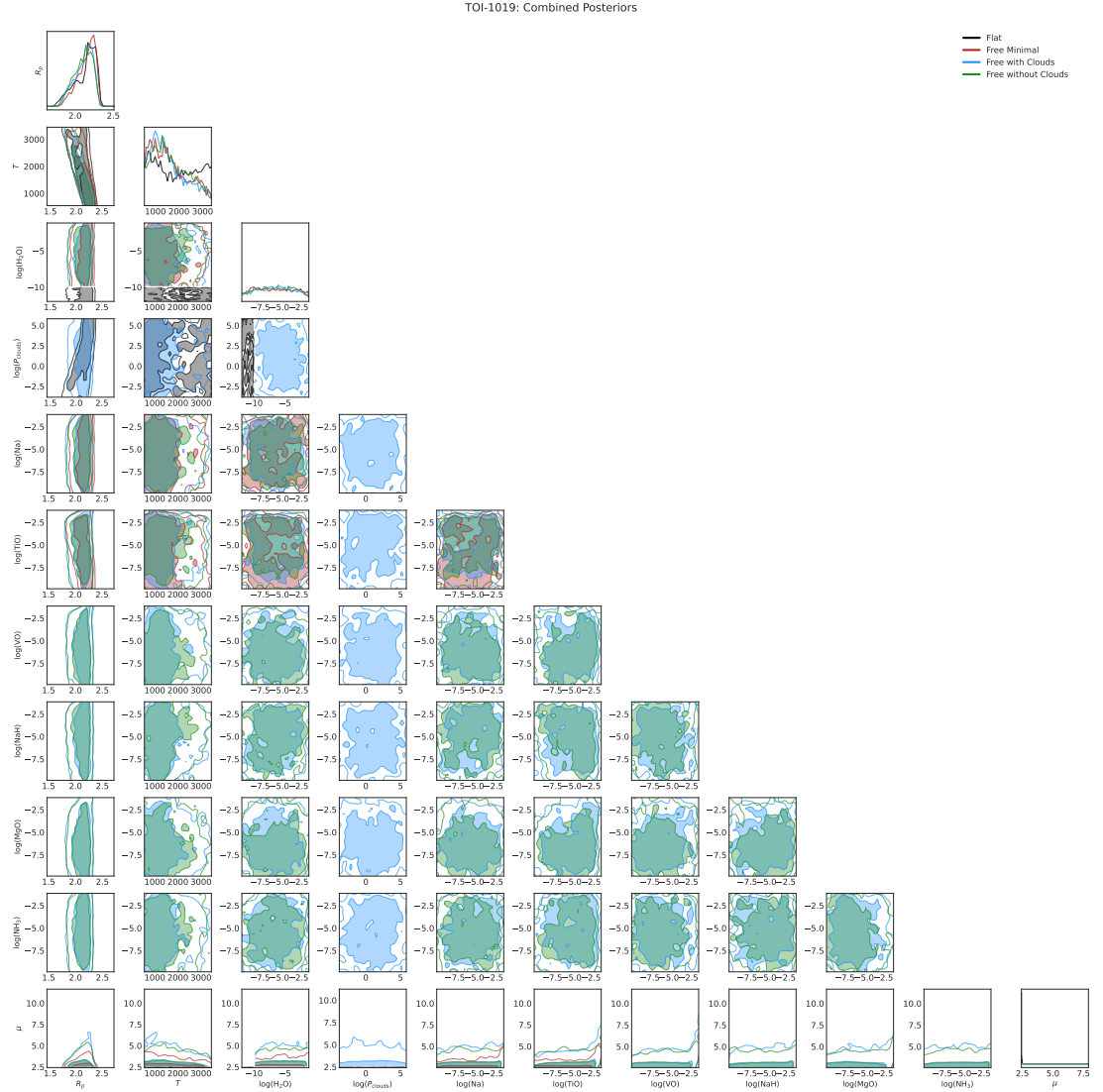


Figure A4.1: Comparison of marginalized posteriors for the four retrieval families. Broad and overlapping posteriors across models, together with the near-equal Bayesian evidences, indicate that the current dataset does not yield statistically decisive constraints on composition or clouds.

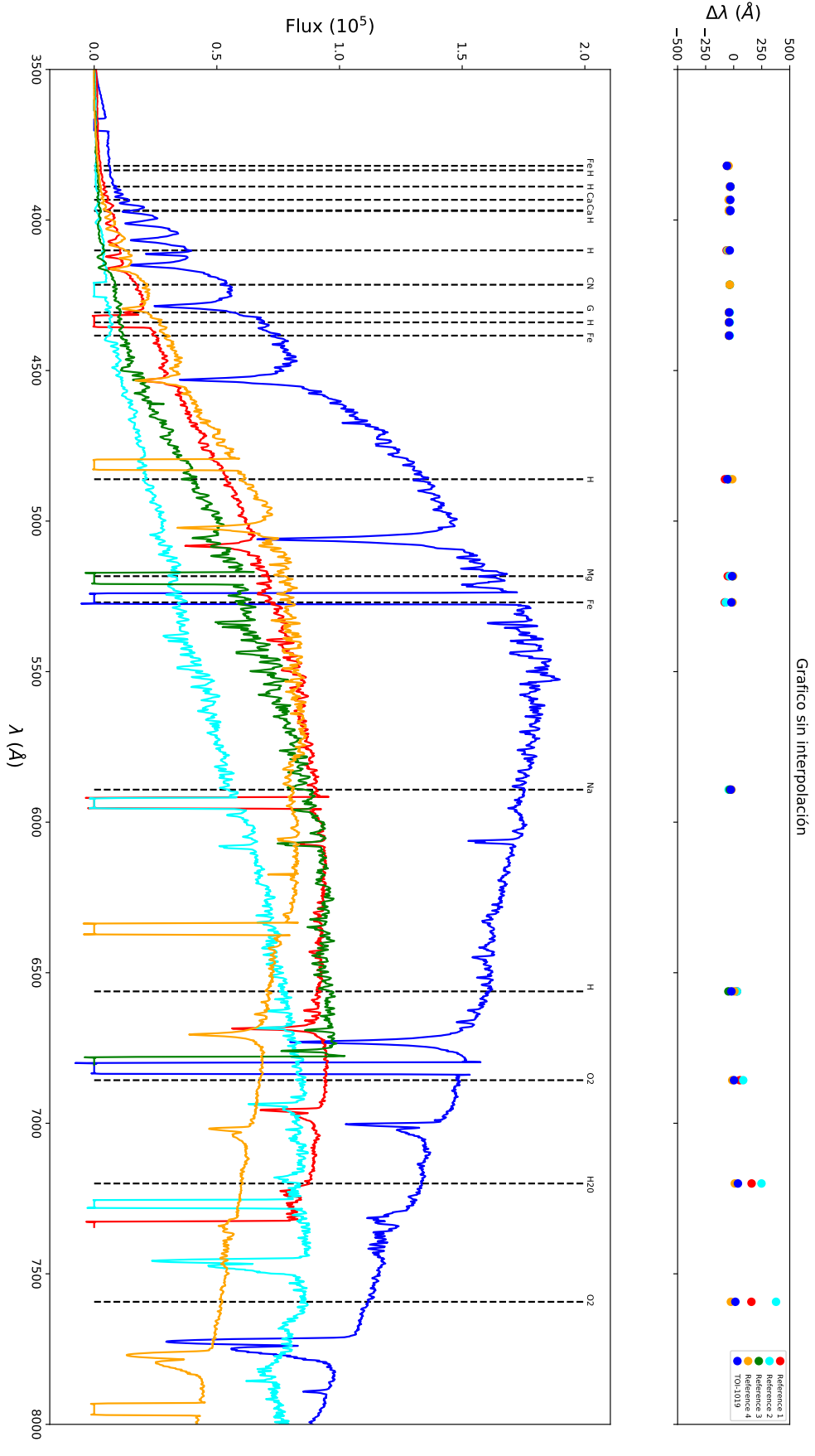


Figure A5.1: One-dimensional spectra of TOI-1019 and the reference stars extracted from the same exposure, before the wavelength alignment and interpolation procedure described in Section 3.4.1. The relative displacement of spectral features between the extracted spectra can be seen in the figure.

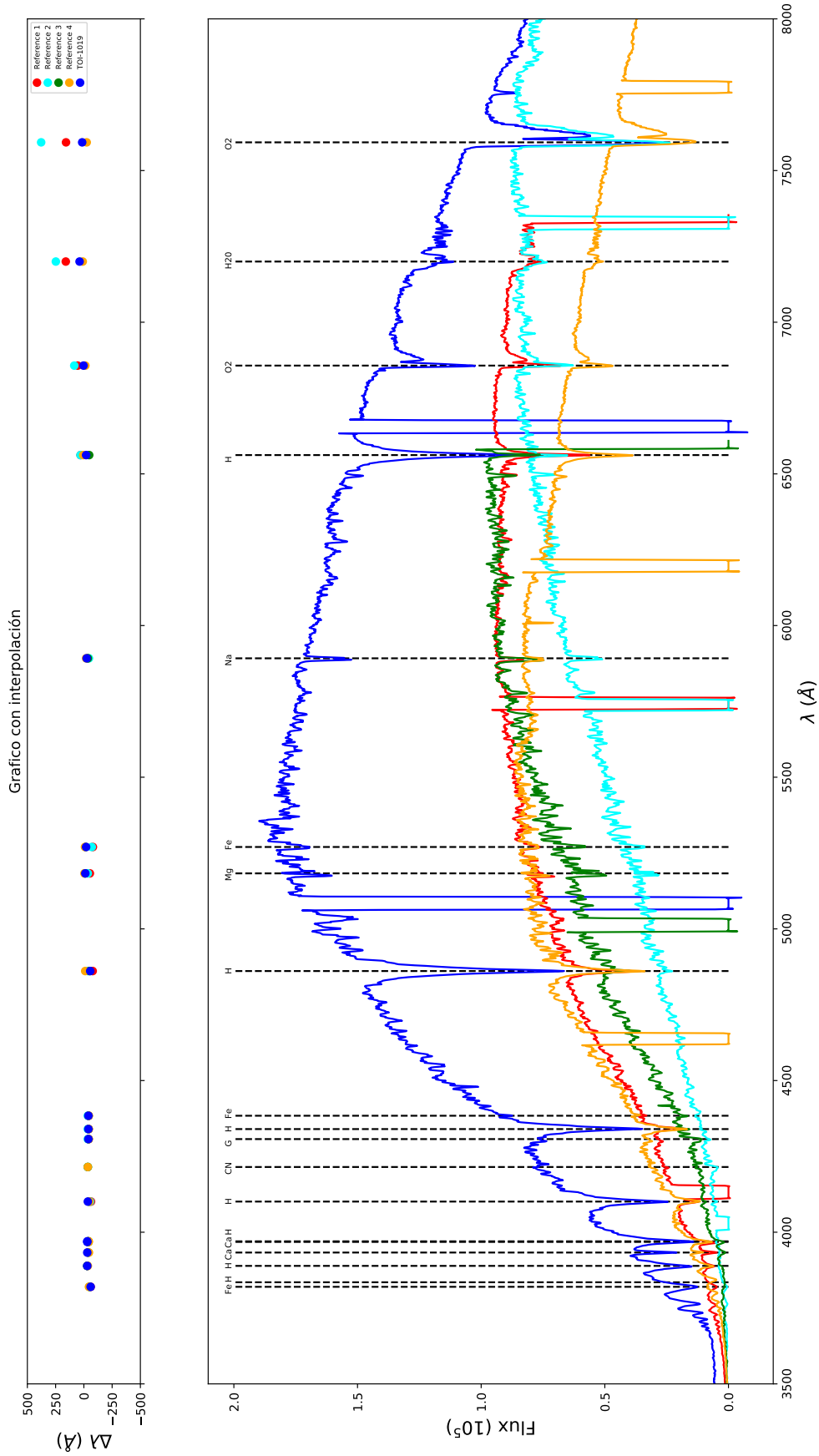


Figure A5.2: Same one-dimensional spectra shown in Figure A5.1, after applying the wavelength alignment and interpolation procedure. The spectra are brought into a common wavelength reference using selected spectral features as reference points.

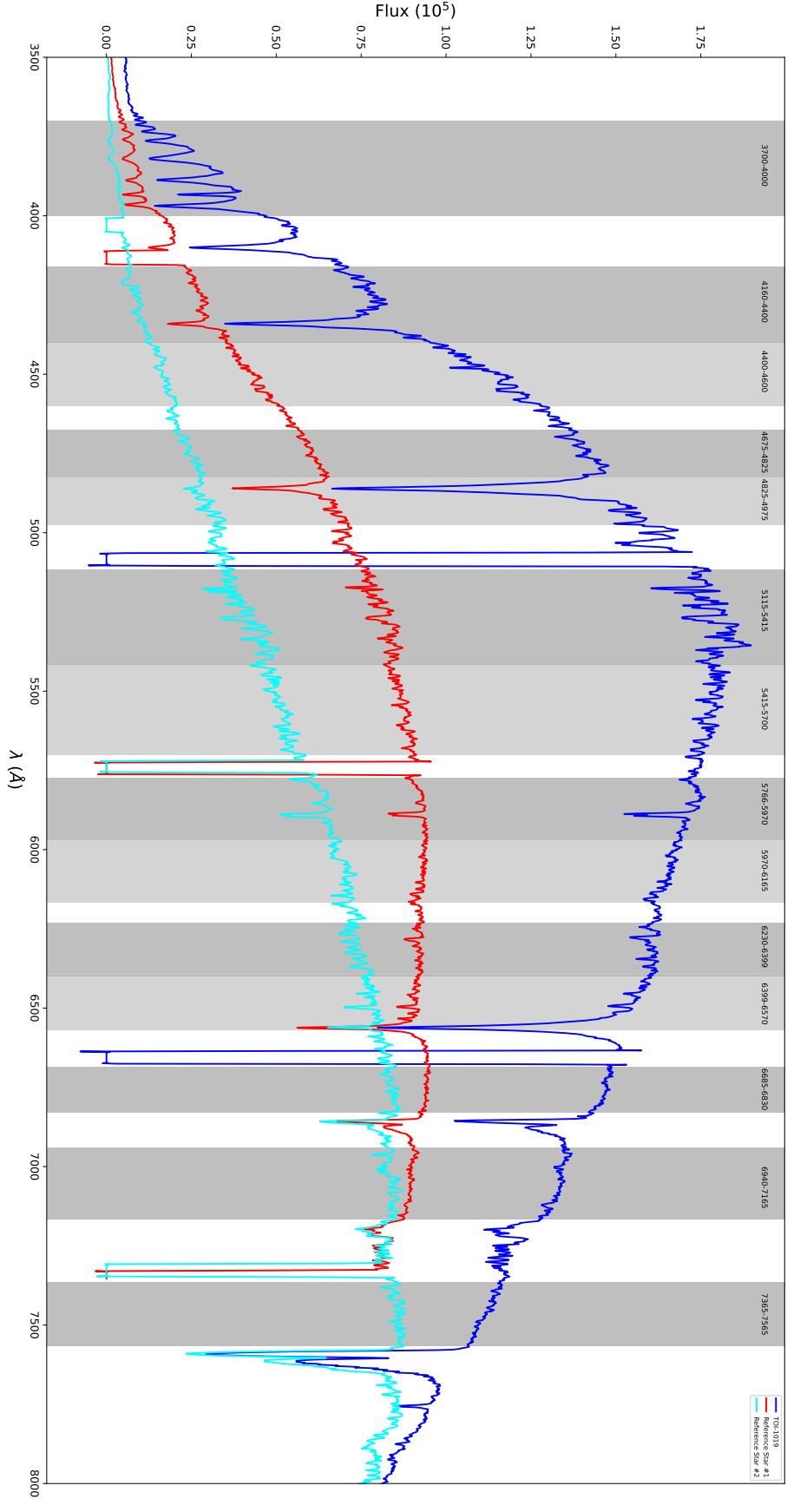


Figure A5.3: Spectra of TOI-1019, and the reference stars #1 and #2 that were kept for the analysis, with the spectrophotometric channels created along the entire wavelength range, displayed as the different gray shaded areas. The colors of each star's spectrum is the same as in Figure 4.5.1.