

Salt and the Sky: Detecting Hydrogen and Sodium in Exoplanetary Atmospheres

by

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“But it is one thing to read about dragons, and another to meet them.”

–URSULA K. LE GUIN, A WIZARD OF EARTHSEA

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Chapter 1

On the Many Rocks Scattered Throughout the Cosmos

Taken as the sum of their parts, our lives do not measure greatly in the face of cosmic time. One of the many reasons we astronomers get into this business is the recognition of that feeling, that our own lifespans are an infinitesimally small blip, that the atoms in our bodies (or indeed, on this pale blue dot as a whole) are an infinitesimally small fraction of what is really out there. We lean into that feeling, reaching into those vast scales, placing ourselves again and again in front of things that we really have no ability to comprehend in their entirety. And in doing so, the knowledge and understanding of our species moves forward, bit by tiny bit, into places it has never been before. So what is a human life, measured up against the Cosmos? So many atoms and 80-ish years, but still a link that can stand on the very edge of what we know about reality, who can push that boundary just a few steps farther for the benefit of an entire world.

1.1 A Brief History of Space

The earliest astronomers were careful observers, marking solstices and predicting eclipses with remarkable precision. In those ancient beginnings lay the first recognition that the heavens followed patterns, that the cosmos had order. For

centuries the Greek-inspired geocentric model endured, until careful measurement began to outweigh philosophical argument. Copernicus displaced Earth from the center. Kepler replaced circles with ellipses. Galileo turned a telescope to the heavens and found mountains on the Moon, moons around Jupiter, and phases of Venus, evidence that those apparitions in the sky were real, physical worlds.

The centuries that followed expanded the scale of that system beyond imagination. The Milky Way was once thought to be the whole of creation, but it became only one galaxy among billions. Spectroscopy revealed that the same atoms found in laboratory flames burn in distant stars. Hubble showed that galaxies recede from one another and that the universe has a beginning in a hot, dense state we now call the Big Bang. The faint glow of the cosmic microwave background confirmed that early fireball, and the abundances of light elements traced nuclear reactions in the first minutes of time.

Today we describe a cosmos 13.8 billion years old, expanding at an accelerating rate, composed mostly of dark matter and dark energy, substances we cannot yet see or fully understand. We map the large-scale structure of galaxies across billions of light years, detect exoplanets orbiting distant stars, and probe atmospheres for hints of biochemistry beyond Earth. We model black hole mergers and the inflationary fluctuations that seeded cosmic structure. We have come a long way.

Astronomy has always been a story of expanding horizons, repeatedly discovering that what we once thought was everything is only a part of something larger. The field has steadily pushed outward, enlarging the Universe that we seek to place ourselves within. We now hold a model of the cosmos that is powerful, and yet still incomplete. And in that incompleteness lies the continuation of the story, the same impulse that led ancient observers to look up, and that now drives us to measure and question the Universe itself.

The ingredients for life are not rare. The question has shifted from whether planets exist to how often environments like our own arise, and more profoundly, what fraction of them proceed from chemistry to biology, and from biology to intelligence. In 1961, Frank Drake proposed a simple framework for thinking about this progression, a way to separate the vast uncertainty of “Are we alone?” into measurable pieces, each tied to astrophysical or biological processes we can begin to quantify. That framework is now known as the Drake Equation, first introduced as the organizing framework for the Green Bank conference, and later appeared in print in Drake (1965):

$$N = R_* f_p n_e f_l f_i f_c L,$$

where N is the number of communicating civilizations in the Milky Way, R_* is the mean rate of star formation, f_p is the fraction of stars with planets, n_e is the mean number of potentially habitable planets per system, f_l is the fraction where life arises, f_i is the fraction where intelligent life evolves, f_c is the fraction that develop detectable communications, and L is the average lifetime of such a civilization.

In recent decades, one of the most powerful tools for addressing these terms has been atmospheric spectroscopy. The Drake Equation asks how frequently life-bearing worlds arise, and spectroscopy provides one of the few direct methods to investigate the physical and chemical environments in which life might emerge (i.e., n_e in the equation above), and potentially the chemical signatures life itself could imprint on a planet. By dispersing starlight that has filtered through or reflected off an exoplanet’s atmosphere, we can measure the presence of specific atoms and molecules, constrain temperature structures, probe atmospheric escape, and assess

habitability conditions. The detection of sodium, hydrogen, water vapor, carbon-bearing species, or more complex molecules can characterize distant worlds, and it also refines the astrophysical terms of the Drake framework by informing us about how common atmospheres are, how they evolve, and whether the chemical pathways necessary for life are plausible elsewhere. In this way, atmospheric spectroscopy bridges cosmology and biology, translating the abstract factors of an equation into measurable physical quantities.

1.2 Know Thyself

Modern exoplanet science is often framed as a search outward, but many of its most practical rules were learned by looking inward. Once “planet” started meaning “any large non-stellar body” instead of just the eight such objects orbiting the Sun, our own system became both a baseline and a potential bias. We have a single example that is extraordinarily information-rich, but also potentially unrepresentative. The Solar System is uniquely valuable because it lets us connect atmospheres, interiors, geology, oceans, magnetospheres, history, and life into one coherent narrative, which is the context we usually lack for exoplanets. In practice, many of the sharpest ideas in exoplanet habitability are really Solar System ideas greatly expanded: how atmospheres are made and lost, how chemistry is regulated by rocks and oceans, and how biosignatures can be generated (or “faked” by physics).

One of the first lessons we can take from our Solar System into the wider universe is that habitability is not an isolated variable. The classical “habitable zone” remains a useful starting point, but many examples from the Solar System show that distance from the Sun is only part of the story. Earth’s long-term climate sta-

bility is strongly related to geochemical feedbacks such as the carbonate–silicate cycle (Walker et al. 1981), while Venus demonstrates how similar starting materials can diverge into runaway greenhouse outcomes (Kasting 1988; Way et al. 2016). Mars teaches that “once habitable” can still mean “not habitable now”: multiple lines of evidence point to ancient liquid water and subsequent atmospheric loss and climatic collapse (Jakosky et al. 2015; Wordsworth 2016). For exoplanets, this translates into a shift in our line of questioning. Rather than asking only if it is in the habitable zone, we increasingly ask whether a planet can retain an atmosphere, maintain temperate surface conditions, and avoid catastrophic water loss over gigayear timescales.

A second lesson is that the search for life is already an atmospheric spectroscopy problem close to home. On Earth, life has reshaped atmospheric composition on geological timescales; oxygen and ozone, for example, are deeply entangled with biology in Earth’s history (Lyons et al. 2014). But the Solar System cautions against simplistic “smoking gun” logic. Many proposed biosignature gases have plausible abiotic pathways under certain conditions, and even oxygen, though so compelling to us on modern Earth, can be produced abiotically via processes like water photolysis and hydrogen escape in particular planetary regimes (Meadows et al. 2018). This is why modern biosignature work emphasizes context. The stellar UV environment, the planet’s bulk composition, redox balance, and the presence of companion gases can help discriminate between biological and abiotic origins (Meadows et al. 2018). In exoplanet terms, the Solar System pushes us toward a “multiple working hypotheses” approach, where the goal is to assemble a self-consistent atmospheric and planetary story.

A third lesson is that the best near-term targets for life may be ocean worlds, instead of direct Earth analogs. Europa and Enceladus sit well outside the classi-

cal habitable zone, yet multiple measurements indicate global subsurface oceans, active chemistry, and energy sources potentially capable of sustaining life (Hand et al. 2020). Enceladus is particularly important because Cassini directly sampled plume material. Evidence includes water vapor, salts, organics, and molecular hydrogen consistent with water–rock reactions that could power chemosynthetic ecosystems (Postberg et al. 2018). These results reshape exoplanet expectations in two ways: first, they expand “where life could be” beyond surface liquid water under sunlight. Second, they highlight the practical reality that life detection is often easier when a world leaks its interior to space (plumes) than when it hides beneath kilometers of ice. For exoplanets, we don’t get plume fly-throughs, but the principle carries over. The most informative systems may be those with observable atmospheric escape, photochemistry, or volcanism that reveal interior–atmosphere coupling.

A fourth lesson is that planetary history matters, and our Solar System provides many examples of how history writes itself into atmospheric composition and dynamics. Our planets can give us detailed information on physical mechanisms like disk chemistry, core formation, volatile retention, late impacts, which we can generalize outward when interpreting worlds we cannot visit (Öberg & Bergin 2021). In exoplanet atmospheric work, this becomes a key question: is an atmosphere a transient layer set by recent escape and irradiation, or a longer-duration archive of formation location, accretion history, and interior evolution?

Finally, the Solar System teaches us how to design the exoplanet search for life. “Follow the water” is still a good starting point, but modern strategy is increasingly becoming more “follow the processes,” as we look deeper into atmospheric loss and replenishment, photochemistry under different stellar spectra, interior outgassing, and the stability of climate feedbacks. This process-driven view is

explicitly reflected in recent community strategy documents, which frame life detection as an end-to-end inference problem requiring atmospheric characterization plus planetary and stellar context, not a one-off detection of any single molecule (National Academies of Sciences, Engineering, and Medicine 2018). In practice, that means that even when exoplanet atmospheric studies focus on seemingly “simple” detections (atoms like Na or signatures of extended hydrogen), they are not trivial problems. They are how we learn the rules governing atmospheric evolution, escape, and chemistry across planet types, which is the scaffolding required before any biosignature claim can be credible.

1.3 The Current Most Prevalent Schemes

1.3.1 Every Rock and Pebble

The modern exoplanet era effectively began in the 1990s, when indirect techniques became precise enough to detect planetary signals against stellar variability and instrumental systematics. The first confirmed exoplanets were found around the pulsar PSR B1257+12 via pulsar timing (Wolszczan & Frail 1992), followed by the first planet discovered around a Sun-like star, 51 Pegasi b, detected using precise radial velocities (Mayor & Queloz 1995). These early detections established that planets are common, but also that the architectures we find are not constrained to look like the Solar System.

As of March 12, 2026, the NASA Exoplanet Archive lists 6,147 confirmed exoplanets, with 760 confirmed *TESS* (the Transiting Exoplanet Survey Satellite, more on this satellite in section 1.3.1) planets and 7,890 *TESS* project candidates. This growth has shifted the field toward population-level questions about planet formation, dynamical evolution, and atmospheric survival. A useful synthesis of

what the current census implies (occurrence rates, orbital architectures, eccentricities, multiplicity, and spin-orbit properties), with an emphasis on close-in exoplanets, is given by Zhu & Dong’s 2021 review. Figure 1.1 demonstrates the discovery by method of confirmed exoplanets per year, as well as a mass-versus-period plot of the exoplanets confirmed so far.

The first chapter of detection was dominated by radial velocity (RV) surveys. RVs measure the star’s line-of-sight motion and constrain orbital period, eccentricity, and a minimum mass. RV detection is most sensitive to massive, short-period planets and naturally favored early hot-Jupiter discoveries.

The second phase was driven by transits, which provide planetary radius and precise ephemerides. Once large photometric surveys were compiled, transits turned exoplanets into a statistical population rather than a handful of special systems. Notably, transits alone do not give mass; the transiting candidates that become benchmark planets usually do so because they can be followed up with spectroscopy (RVs and the Rossiter-McLaughlin (RM) effect; see below).

With thousands of planets, several demographic trends are now well established. One of the clearest is the radius gap (“radius valley”) in the distribution of close-in small planets: Fulton et al. (2017) showed a deficit around roughly $1.5\text{--}2.0 R_{\oplus}$, often interpreted as evidence that atmospheric loss and/or formation pathways split planets into rocky cores and slightly larger planets retaining H/He envelopes. A broader context for these trends, including how occurrence and architecture depend on stellar type, orbital distance, and multiplicity, is well summarized in the Winn & Fabrycky 2015 review and discussed with reference to the more recent Kepler mission in Zhu & Dong’s 2021 review.

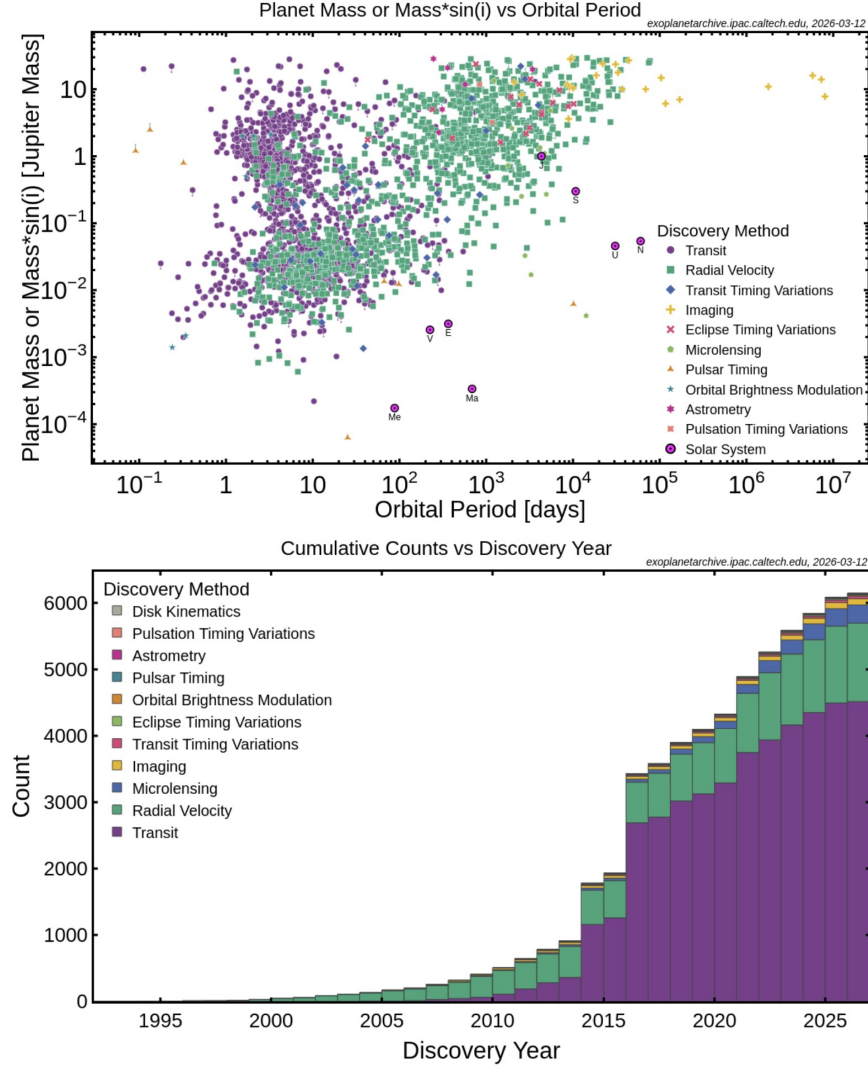


Figure 1.1: From the NASA Exoplanet Archive. *Top:* Planet mass versus orbital period, including all confirmed exoplanets thus far as well as discovery method. Note clumps that may represent observational biases or potentially real patterns. *Bottom:* Cumulative exoplanets discovered per year, colored by discovery method.

The Neptune Desert

One of the more striking population-level features to emerge from the exoplanet census is the Neptune desert (sometimes referred to as part of the “sub-Jovian desert”). Simply put, there exists a dearth of Neptune-size/Neptune-mass planets on very short-period orbits. Mazeh et al. (2016) defined and quantified this phenomenon in both the period–mass and period–radius planes, emphasizing that it is not simply explained as a selection effect because Neptunian planets are often detected at slightly longer periods. The desert sits between two very different close-in populations: hot Jupiters (which can survive extreme irradiation) and super-Earths/mini-Neptunes (many of which either never accreted or later lost substantial gaseous envelopes). Figure 1.2 shows the Neptune desert delineated on the mass/period and radius/period planes.

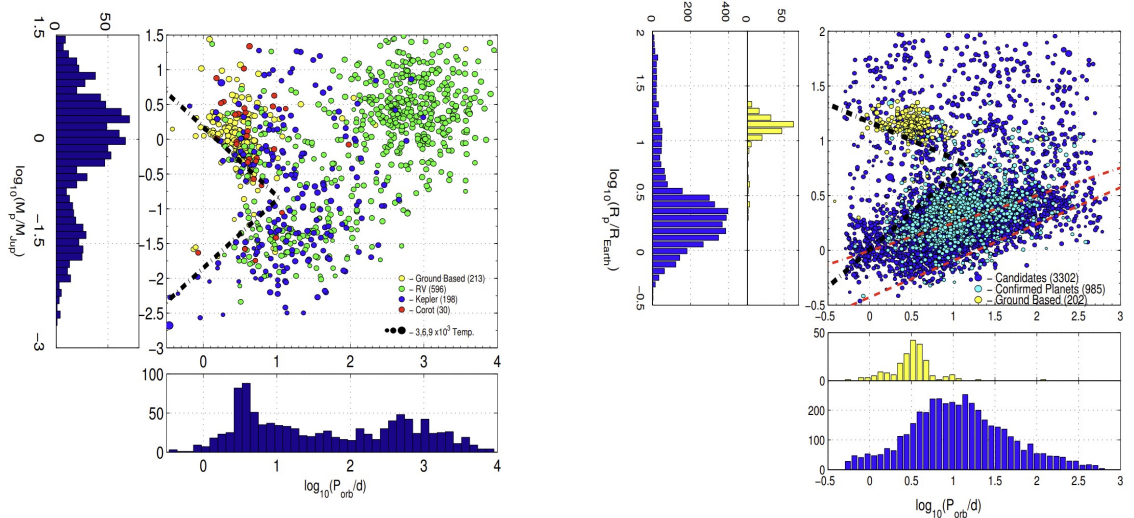


Figure 1.2: From Mazeh et al. (2016) *Left:* The Neptune Desert in the mass/period plane, outlined by the dashed black lines. *Right:* The Neptune Desert in the radius/period plane, also outlined in dashed black. In both panels, the relative paucity of detected planets within the “desert” region is apparent.

The leading physical interpretations of the Neptune desert tend to involve a

competition between migration and atmospheric mass loss. If a sub-Jovian planet reaches very high irradiation early in its existence, strong photoevaporation can remove a large fraction of its H/He envelope, potentially leaving behind a smaller-radius core and thereby moving the planet from the Neptune-radius regime. At the same time, dynamical processes (especially high-eccentricity migration followed by tidal circularization) can impose additional boundaries by restricting which planets can survive close passages without being tidally disrupted, helping to shape the upper edge of the desert in period–mass space (Owen & Lai 2018).

The Neptune desert is, in effect, a population-scale signpost that irradiation, escape, and migration can reshape planetary classes and change what we observe. That makes it a useful bridge between detection demographics (what planets exist where) and atmospheric physics (what processes allow atmospheres to persist or be removed), especially when motivating projects focused on hot, highly irradiated planets and light-element tracers of extended or escaping atmospheres.

The *Transiting Exoplanet Survey Satellite* (*TESS*)

The modern era of exoplanet discovery required instruments built to watch enormous swaths of sky patiently and repeatedly. Among the most important of these is the *Transiting Exoplanet Survey Satellite* (*TESS*), designed to search bright, nearby stars for the periodic dips in light produced by transiting planets, thereby turning discovery into a pipeline for follow-up mass measurements, spin-orbit studies, and atmospheric characterization. The baseline mission strategy observes the sky in $24^\circ \times 96^\circ$ sectors, typically 27 days per sector, with much longer coverage near the ecliptic poles (“continuous viewing zones”). Its four-camera design and observing strategy are laid out in the core mission paper (Ricker et al. 2015). Because *TESS* targets are bright, the planets are well suited for precision

RV mass measurements (density and composition constraints), high-resolution imaging (to rule out blends/companions), and time-series transit spectroscopy (RM and, using the same data, atmospheric transmission spectroscopy).

Follow-up spectroscopy is usually motivated first by dynamics. Radial velocities confirm the planet’s mass scale, reveal additional companions, and check for stellar activity-induced impostors. But time-series spectroscopy during transit is commonly pursued for the Rossiter–McLaughlin effect, which constrains the projected spin–orbit angle, or projected obliquity.

The RM effect appears during every transit. When a planet moves in front of a star, throughout its transit it will block some of the light from the side of the star rotating towards us (on Earth) and then later block light from the side rotating away (in the case of a pro-grade orbit). Because the measured stellar radial velocities are so sensitive to changes in the Doppler reddening of the star’s light, the planet blocking a statistically significant percentage of either the red- or blue-shifted light creates a characteristic “wave” in the RV transit plot (see Figure 1.3). If the orbit of the planet is misaligned to the spin axis of the star, it will block more of one side of the star during its transit, resulting in an asymmetric RM wave. Gaudi & Winn (2007) provide a clear discussion of the RM signal and its use for confirmation and geometry. In practice, RM modeling depends on how RVs are extracted (cross-correlation, iodine cell, stabilized spectrographs), and analytic formalisms exist for common pipelines (Boué et al. 2013).

Rossiter-McLaughlin measurements matter because they probe dynamical history. Strong misalignments can point to migration or dynamical excitation pathways that differ from smooth disk migration, and they are especially informative for hot Jupiters. Figure 1.3 shows how the RM effect appears in the radial velocity measurements during transit.

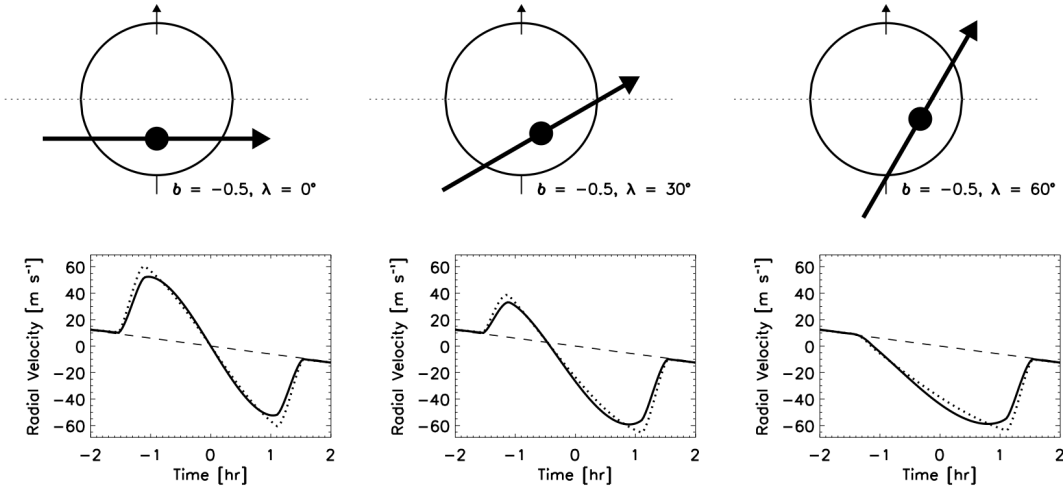


Figure 1.3: RM Effect from Winn (2014). Different spin-orbit geometries produce different RM curves in the radial velocity data.

1.3.2 Atmospheric Analysis

Atmospheric characterization is now a mature branch of exoplanet science, as the field is increasingly able to constrain atmospheric composition, thermal structure, and key evolutionary processes, rather than just asking whether an atmosphere exists. The principal observables come from transmission spectroscopy and emission spectroscopy (secondary eclipses) with a clear overview of the methods and major degeneracies given by Madhusudhan (2019).

Transmission spectroscopy is conceptually straightforward: light from the star passes through the planet's limb on its way to us, imprinting upon the spectrum wavelength-dependent absorption, evidence of the chemical species within that planet's atmosphere. The basic theoretical framework for transmission spectra in transiting giant planets was established early (Seager & Sasselov 2000), and the method was validated observationally by landmark detections such as sodium absorption in the hot Jupiter HD 209458b (Charbonneau et al. 2002). Since then, we

have acknowledged that interpretation is often limited by photon noise and degeneracies between composition, clouds/hazes, and the atmospheric mean molecular weight, which sets the scale height and therefore the amplitude of spectral features (Di Maio et al. 2023). A canonical example is GJ 1214b, where high-quality *Hubble Space Telescope* (*HST*) data yielded a largely featureless transmission spectrum, strongly suggesting aerosols obscuring deeper layers (Kreidberg et al. 2014).

Transmission spectra obtained at high spectral resolutions are able to resolve individual lines and exploit Doppler shifts to separate planetary signals from tellurics and the stellar spectrum. One well-known example detected CO in HD 209458b and used the planet’s orbital velocity to constrain system parameters and infer high-altitude winds (Snellen et al. 2010). At these resolutions, careful treatment of stellar contamination (e.g., center-to-limb variation (CLV) and RM-related line-profile changes) can be important for robust atmospheric line measurements (Casasayas-Barris et al. 2020). The most recent change in broad-band atmospheric constraints, however, is the *James Webb Space Telescope* (*JWST*), which provides wide wavelength coverage and high precision, enabling multi-species constraints that reduce long-standing ambiguities, as illustrated by early *JWST* transmission results for WASP-39b (Rustamkulov et al. 2023).

A second major theme is atmospheric evolution, particularly escape. Highly irradiated planets can sustain extended upper atmospheres and hydrodynamic outflows, and light elements are often the most direct tracers of these processes. The detection of metastable helium at 10,833 Å in WASP-107b provided a widely used near-IR probe of escape (Spake et al. 2018), and atmospheric escape is now recognized as a key evolutionary mechanism for close-in planets, shaping individual atmospheres and population-level features (Owen 2019).

This thesis is positioned within that context. Hot Jupiters remain among

the most information-rich targets for transmission spectroscopy because their low mean molecular weight atmospheres and large scale heights make atomic features measurable, and intense irradiation makes escape-related physics observationally accessible. By focusing on light-element tracers (e.g., Na and H α) in high-resolution transmission spectra, this work aims to put empirical constraints on atmospheric structure and escape in strongly irradiated giant planets, linking individual detections and non-detections to the broader picture of atmospheric evolution.

1.4 This Project

The systems TOI-1288 and TOI-640 provide complementary test cases for the central measurement problem of this thesis: under what conditions are atomic species detectable in transmission, and what does a detection or non-detection imply about atmospheric structure and evolution? Both systems were identified by *TESS* and then characterized with intensive spectroscopic follow-up, yielding the kind of time-series, high-resolution spectra that can be used for both dynamical confirmation and transmission spectroscopy (Knudstrup et al. 2022; Rodriguez et al. 2021; Knudstrup et al. 2023). They are situated between the population-level question of how irradiation sculpts planets and feasible observational questions, like what atmospheric tracers are measurable with current data.

TOI-1288 is particularly valuable because its inner planet, TOI-1288b, is a short-period super-Neptune that lies in the Neptunian desert (Mazeh et al. 2016). The system characterization by Knudstrup et al. (2022) established TOI-1288b as a transiting super-Neptune on a ~ 2.7 -day orbit, with an outer Saturn-mass companion on a much longer period. Subsequent uniform radial-velocity analysis

within the *TESS*–Keck Survey further refined system parameters and provides a consistent mass scale within a large comparative sample (Polanski et al. 2024). From the perspective of atmospheric evolution, TOI-1288b’s location in the desert makes it a direct probe of the physical processes thought to remove or reshape close-in gaseous envelopes. In particular, hydrodynamic escape driven by extreme irradiation is expected to be most consequential for low- to intermediate-mass planets, potentially stripping H/He envelopes and sculpting observed population features (Owen 2019). A key interpretive question for TOI-1288b is therefore whether its atmosphere retains measurable atomic signatures or whether the relevant species are muted by depletion, high mean molecular weight, or escape-driven evolution.

TOI-640b occupies an equally instructive regime: it is a low-density, inflated hot Jupiter on a ~ 5 -day orbit, first presented as part of the *TESS* hot-giant yield (Rodriguez et al. 2021). The system is also dynamically and geometrically distinctive. Time-series spectroscopy during transit enabled a Rossiter–McLaughlin measurement showing TOI-640b on an extreme (nearly polar) orbit (Knudstrup et al. 2023). This combination of large atmospheric scale height (favorable for transmission signals) and unusually constrained orbital geometry (informative about system history) makes TOI-640b a good target for atomic measurements.

The observational questions pursued in this thesis are intentionally narrow and physically diagnostic. Alkali metals such as Na are among the most accessible atomic tracers at optical wavelengths, and a robust Na detection generally indicates that the lower atmosphere is extended enough for line cores (and in favorable cases wings) to imprint measurable absorption. Hydrogen traced through $H\alpha$, by contrast, is primarily sensitive to excited populations in the upper atmosphere and can act as a probe of high-altitude thermosphere physics and (in some regimes) es-

cape. Non-detections are therefore informative. A Na non-detection can indicate muted scale height, clouds/hazes, or insufficient S/N, while an H α non-detection can constrain the degree of excitation and the strength of any extended hydrogen layer. By applying a consistent high-resolution transmission-spectroscopy analysis to both systems, this work aims to determine which atomic species are measurable in practice for a super-Neptune in the Neptunian desert and for an inflated hot Jupiter, and to interpret detections and upper limits in the broader context of irradiation-driven atmospheric evolution.

Chapter 2

Observational Techniques

The primary goal of the *Transiting Exoplanet Survey Satellite* (*TESS*) is to discover exoplanets via the transit method; it monitors nearby stars for the periodic dimming associated with a planet passing in front of the star on a regular orbit (Ricker et al. 2015). Upon detecting one of these characteristic dips in flux, a pipeline identifies the source as a *TESS* Object of Interest (TOI) along with a numerical designation. The spacecraft observes one sector (a 96 x 24 degree strip of the sky, owing to its four wide-field CCD cameras lined up in a row) for 27 days at a time before moving to the next sector, thereby covering almost the entire celestial sphere in the first two years of operation (August 2018–2021). *TESS* primarily targets nearby bright stars that are ideal for follow-up observations by more targeted instruments such as the *James Webb Space Telescope* (*JWST*). The satellite lays the foundation for planetary discovery and follow up-studies, including atmospheric characterization.

The alert for TOI-1288b was issued in late 2019, when transit signals were detected by the SPOC pipeline in combined sector data (sectors 15–18). Knudstrup et al. (2022) then formally confirmed the planetary nature.

TOI-640b was identified as a candidate in early 2019 (sectors 6 and 7), whereafter the discovery and confirmation were published by Rodriguez et al. (2021). Subsequent *TESS* observations in Sectors 33 and 34 (2020 Dec – 2021 Feb) pro-

vided higher-cadence data used by Knudstrup et al. (2023). Figure 2.1 shows the phase-folded lightcurves for TOI 1288b and TOI 640b as retrieved by Knudstrup et al. (2022) and Knudstrup et al. (2023), respectively.

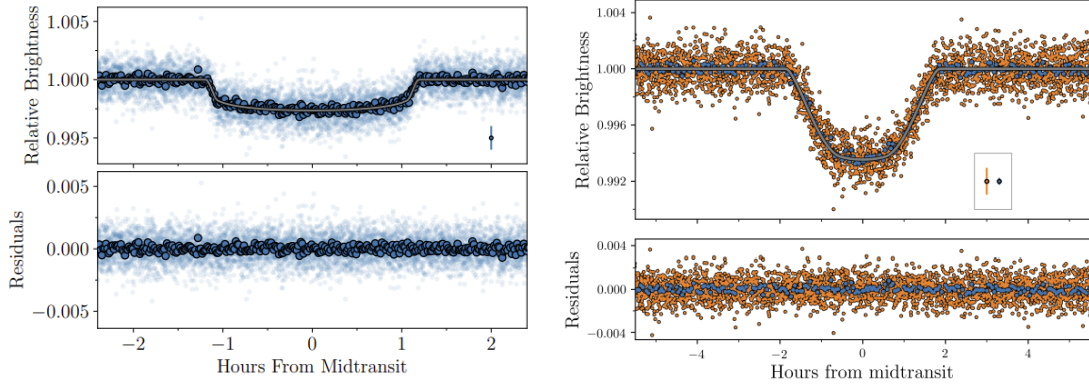


Figure 2.1: Phase-folded *TESS* transit light curves for TOI-1288b (left) and TOI-640b (right).

While *TESS* photometry revealed the transit signatures of both TOI-1288b and TOI-640b, confirming and characterizing these systems required high-resolution spectroscopic observations. Spectroscopy serves several complementary roles in exoplanet studies: validating the planetary nature through radial-velocity (RV) variations, deriving stellar parameters, and, during transits, probing the spin-orbit geometry through the Rossiter-McLaughlin effect and measuring absorption from the planetary atmosphere.

For both systems, out-of-transit spectroscopy was used to measure the stellar reflex motion (stellar radial velocity) in order to derive the mass of the planets and to rule out false-positives, such as stellar binaries, and to derive orbital parameters.

2.1 TOI 1288b: Discovery and Data

The observational campaign for TOI-1288b combined precision space-based photometry from *TESS* with multi-site ground-based transit follow-up, high-resolution speckle and adaptive-optics imaging, and high-dispersion spectroscopy using the High Accuracy Radial velocity Planet Searcher for the Northern hemisphere (HARPS-N), the High Resolution Echelle Spectrometer (HIRES), and the Fiber-fed Echelle Spectrograph (FIES), respectively. This multi-technique approach made for robust planet validation, allowed removal of potential false positives from blended sources, and yielded the system’s orbital and physical parameters through joint light-curve and RV modeling, in the process creating a dataset that makes it possible to measure the atmospheric properties of the planet. Photometry and high-res imaging are discussed only lightly here, as the bulk of this project is concerned with data from high-resolution spectroscopy.

2.1.1 Photometry (Space and Ground-Based)

In the case of TOI-1288, the *TESS* pipeline detected a ~ 0.25 percent periodic transit every 2.7 days, marking the system as a strong planet candidate.

For the study conducted by Knudstrup et al. (2022), the *TESS* light curves were reprocessed to ensure high internal consistency and to mitigate correlated noise that could affect the transit depth, duration, or timing. Using the `lightkurve` package, a 5σ outlier rejection was applied. Remaining time-correlated noise was handled through Gaussian-process detrending, yielding a cleaned, high-precision photometric time series (Figure 2.2). These data provide the foundation for determining the planet’s orbital period, transit ephemeris, and approximate radius

ratio, and for constraining the system geometry in later joint modeling.

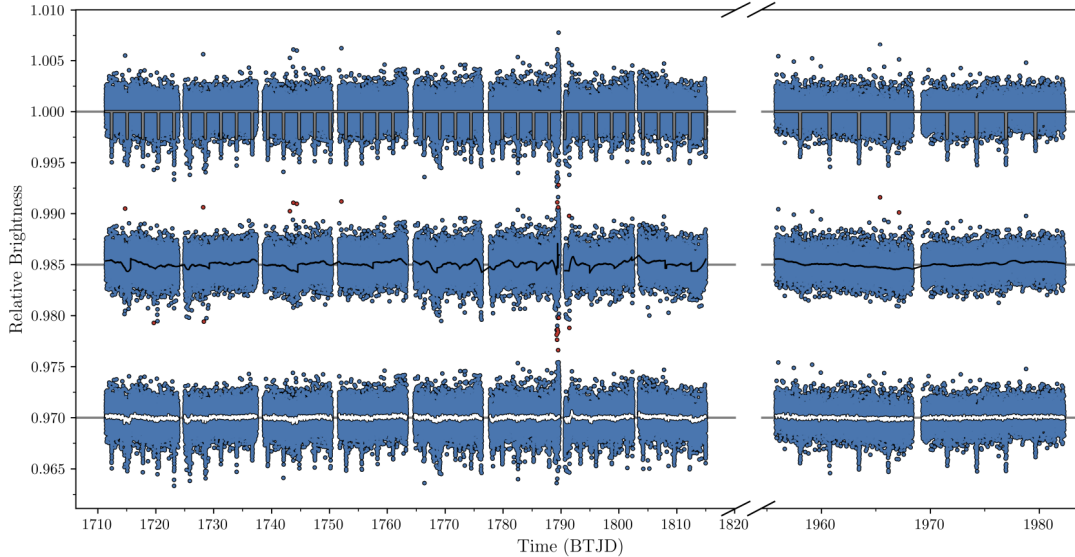


Figure 2.2: 1288 photometry.

A network of ground-based facilities obtained higher-spatial-resolution photometry and transit curves in multiple filters, done in order to address dilution from nearby sources and because instrumental artifacts or background eclipsing binaries can mimic transit-like signals.

The ground-based follow-up verified that the transit originates from the target star, rather than a nearby contaminant or eclipsing binary. The reduced data confirmed the depth, duration, and timing of the *TESS* transits and improved constraints on the ephemeris and transit shape.

2.1.2 High-Resolution Imaging

High-resolution imaging was obtained for TOI-1288 to determine whether unresolved stellar companions could contaminate the *TESS* photometry or mimic a planetary transit. Because *TESS* pixels are large (21 arc-seconds each), even faint

nearby sources within the photometric aperture can contribute flux that alters the measured transit depth or, in the worst case, produce a false positive if the contaminating source is an eclipsing binary. For this reason, high-angular-resolution follow-up is an essential component of transit validation. Figure 2.3 shows the *TESS* image of TOI 1288.

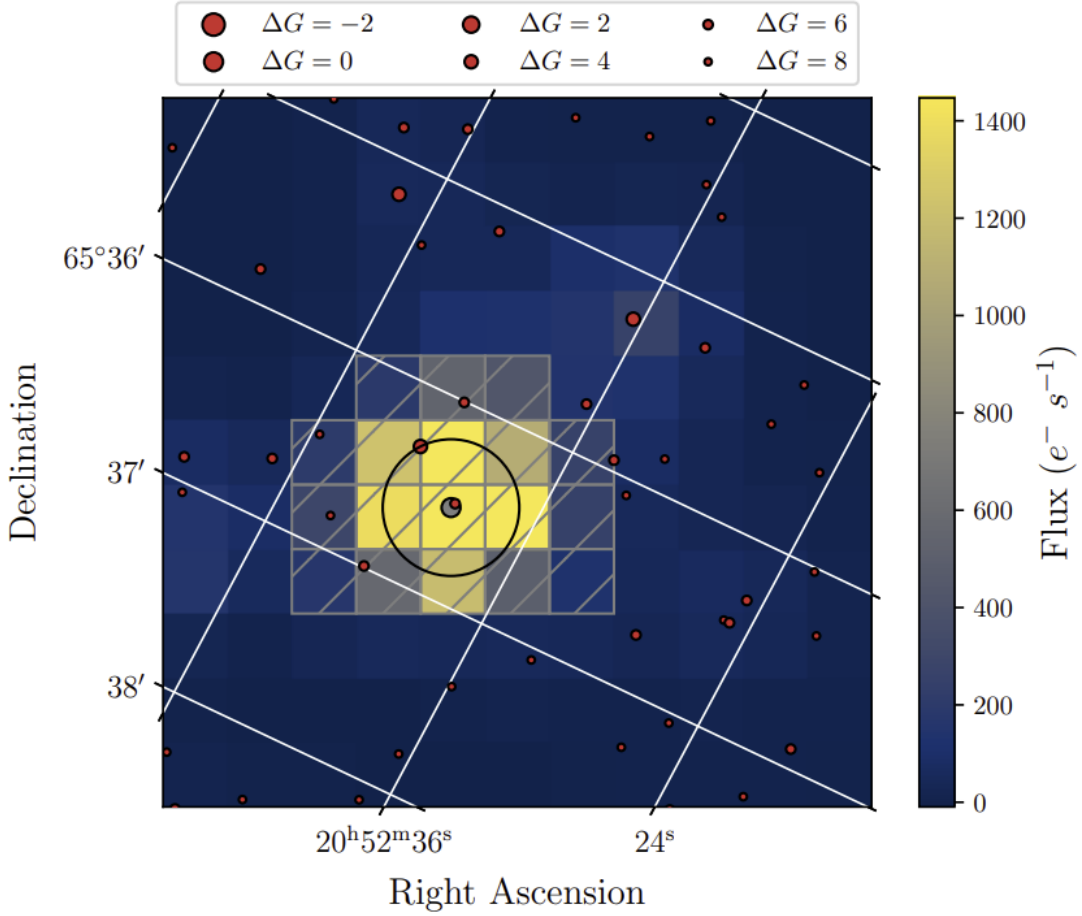


Figure 2.3: *TESS* image of TOI 1288 from sector 15. The grey dot is TOI 1288 itself, and the red dots are nearby sources, the brightest and closest of which has a separation distance denoted by the black circle. From Knudstrup et al. (2022)

Across all observations, no stellar companions were identified at separations or contrasts capable of influencing the *TESS* or ground-based follow-up photometry. Gaia DR3 reports only one nearby source within the *TESS* aperture: a ~ 16 th-

magnitude object $\sim 1.5''$ southwest of TOI-1288, which is far too faint to account for the observed 0.25 percent transit depth. The combined constraints demonstrate that flux dilution in the *TESS* light curve is negligible, and that the transit event originates from the target star rather than from a blended or background eclipsing system.

2.1.3 High-Resolution Spectroscopy

High-resolution spectroscopic observations were obtained to confirm the planetary nature of TOI-1288 b, characterize its orbital properties, and determine the physical parameters of the host star. Radial-velocity measurements provide the dynamical confirmation required to distinguish genuine planetary transits from eclipsing binaries or blended stellar systems, while high-resolution stellar spectra allow precise derivation of the stellar atmosphere parameters that give radius and mass estimates for both star and planet.

Three spectrographs contributed to the overall characterization of the TOI-1288 system. Initial reconnaissance spectra were acquired with FIES on the 2.56 m Nordic Optical Telescope. These observations were used primarily for stellar classification and to rule out large-amplitude radial-velocity variations indicative of an unrecognized stellar companion. The primary RV dataset was obtained with HARPS-N on the Telescopio Nazionale Galileo, which provided 57 high-resolution spectra ($R \approx 115,000$) collected between 2019 and 2022, with individual exposure times ranging from 1,200 to 2,700 s and a median signal-to-noise ratio of roughly 60 per resolution element. R is the resolving power of a spectrograph, defined as $R \equiv \lambda/\Delta\lambda$, where $\Delta\lambda$ is the smallest wavelength interval that can be distinguished at wavelength λ . Large R is essential in high-resolution spectroscopy because it

allows closely spaced spectral features to be separated and very small Doppler shifts to be measured, both of which are critical for precise radial-velocity work and for resolving narrow atmospheric absorption lines.

Precise RVs were extracted using the TERRA (Template-Enhanced Radial velocity Re-analysis Application) pipeline, which performs template-matching to track sub- m s^{-1} -level Doppler shifts. An additional set of 28 spectra was acquired using HIRES on Keck I during 2019–2021. These data, obtained at a median $S/N \approx 72$, were processed using iodine-cell forward modeling, which constrains wavelength calibration, line-spread function, and Doppler shift.

Radial-velocity modeling of the combined HARPS-N and HIRES time series confirmed the 2.7-day period corresponding to the transiting planet, and also revealed a longer-period (~ 443 d) Doppler signal consistent with an additional outer planet in the system. Periodogram analyses, particularly the Generalized Lomb–Scargle periodogram, were used to assess the significance of these signals and to identify any aliases or activity-related periods. To ensure that stellar variability did not masquerade as planetary signals, activity indicators such as line-bisector spans, Ca II H&K indices, and $H\alpha$ measurements were examined alongside the RVs, which are shown in figure 2.4.

In addition to radial-velocity measurements, the HARPS-N spectra were used to determine the fundamental stellar parameters. A co-added high- S/N HARPS-N spectrum was modeled using SME (Spectroscopy Made Easy) and the ARIADNE spectral-fitting framework to derive the stellar effective temperature, surface gravity, metallicity, and projected rotational velocity. These parameters served as inputs for stellar-evolution modeling, which yielded the stellar radius and mass adopted in the planetary characterization.

The stellar parameters are important because nearly every planetary quantity

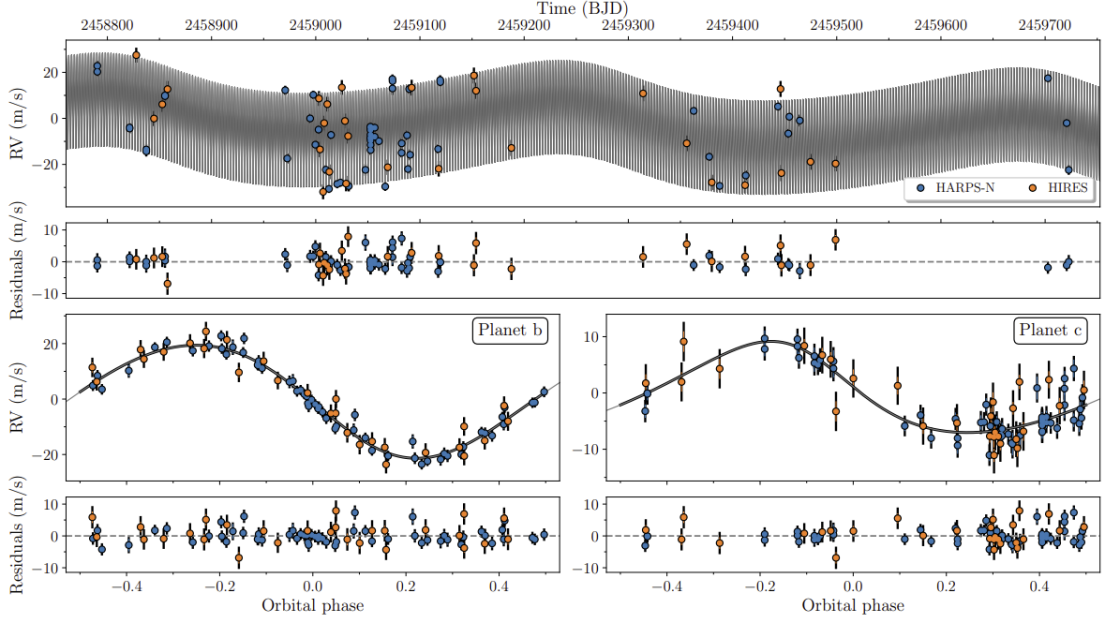


Figure 2.4: *Top:* The HARPS-N (blue) and HIRES (orange) radial velocities as a function of time. The grey model shows the combined signal for planets b and c. The lower plots show RVs phased to planets b and c, with other signals subtracted. From Knudstrup et al. (2022)

in this thesis is measured relative to the host star. The stellar radius and mass set the scale for the planet’s radius and mass, while the effective temperature and metallicity provide the context needed for stellar-evolution modeling, estimates of the irradiation environment, and interpretation of the atmospheric measurements. The projected rotational velocity is also directly relevant for understanding line broadening and for modeling spectroscopic transit effects such as the Rossiter–McLaughlin signal, making accurate stellar characterization a necessary foundation for both the bulk-planet parameters and the transmission-spectroscopy analysis that follows.

For this project, I used the series of 1800s exposures taken on 2020 July 21 through the HARPS-N instrument. More details can be found in the Analysis chapter, but Figure 2.5 shows the full stellar spectrum from one out-of-transit

exposure, representative of the others.

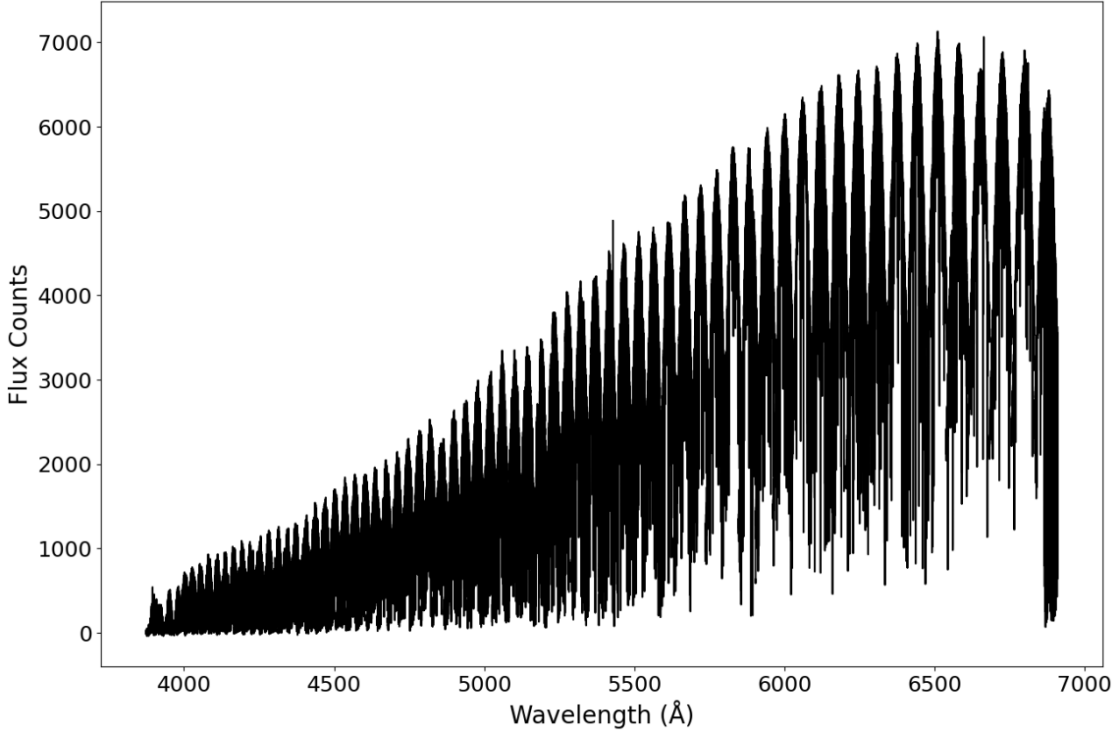


Figure 2.5: The original, raw stellar spectrum of TOI 1288 obtained from the HARPS-N instrument on the 3.58 m Telescopio Nazionale Galileo (TNG) at the Roque de los Muchachos Observatory on La Palma, Spain. Note that the blaze functions in each of the 69 orders are apparent, and make it very difficult to pick out individual lines at this scale.

2.2 TOI 640b: Discovery and Data

TOI-640 b was first identified by *TESS* as a transiting hot Jupiter around an F-type subgiant star. The initial characterization of the planet was again done with multiple instruments through photometric and spectroscopic follow-ups.

2.2.1 Photometry

TOI-640 was first monitored by *TESS* during Sectors 6 and 7, observed between December 2018 and February 2019 at a 30-minute cadence. A periodic transit signal was identified at 5.0038 days, exhibiting a characteristic depth of approximately 0.9 percent, consistent with a Jupiter-size object orbiting a slightly evolved F-type star. These transits were clearly detected in both sectors, with consistent depths and durations. Figure 2.6 shows the *TESS* light curve that indicated the discovery of the planet TOI 640b.

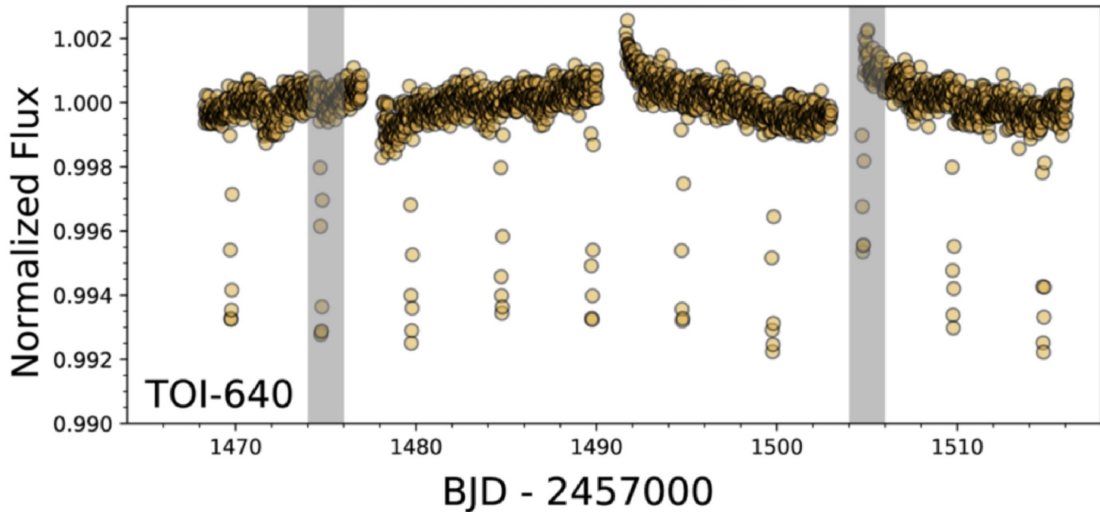


Figure 2.6: Raw *TESS* 30 minute light curve for TOI 640, from Rodriguez et al. (2021)

To validate that the signal originated from the target star rather than an unresolved background object in the relatively large *TESS* pixel scale, TOI-640 was subsequently observed as part of the *TESS* Follow-up Observing Program. Several ground-based facilities acquired higher-spatial-resolution and multi-band photometry. The ground-based transit detections confirmed that the event occurs on the host star and that the transit depth shows no significant wavelength dependence, ruling out blended eclipsing binaries and chromatic false positives.

The combined *TESS* and TFOP photometry thereby establishes the 5-day periodicity, on-target origin, and approximate radius ratio of the companion, forming the basis for the radial-velocity and spectroscopic follow-up.

2.2.2 High-Resolution Imaging

As discussed in section 2.1, high-resolution imaging is a standard component of *TESS* follow-up, used to identify unresolved nearby sources within the large *TESS* pixel scale and to quantify any potential flux dilution. TOI-640 underwent the same validation procedures.

Speckle imaging and adaptive-optics (AO) imaging were obtained to search for close stellar companions at sub-arcsecond separations. The speckle data provide diffraction-limited sensitivity in the optical, while AO imaging extends this sensitivity into the near-infrared, where any cool bound companion would be comparatively brighter. Contrast curves derived from these observations demonstrate that no nearby stars are present at separations or brightness levels capable of influencing the *TESS* photometry or mimicking the 0.9 percent transit depth.

Combined with the Gaia catalog information for the field, the imaging rules out both background eclipsing binaries and bound companions over the spatial scales relevant to the *TESS* aperture. As a result, dilution corrections for TOI-640's transit depth are negligible, and the photometric signal can be confidently attributed to the host star.

2.2.3 Spectroscopic Confirmation

As with TOI-1288 b, high-resolution spectroscopy was obtained to confirm the planetary nature of the *TESS* transit signal and to measure the radial-velocity

variations induced by the orbiting companion. TOI-640 was first observed with the Tillinghast Reflector Échelle Spectrograph (TRES) for reconnaissance, which confirmed that the host star is a single, rapidly rotating F-type subgiant and showed no large-amplitude radial-velocity variations that would indicate a stellar eclipsing binary.

Precise radial velocities were subsequently obtained using several high-resolution spectrographs, including FEROS (Fiber-fed Extended Range Optical Spectrograph), HARPS, CORALIE (not an acronym, named after the baby daughter of an engineer from the Observatoire de Haute-Provence), and CHIRON (also just the name of the instrument). These instruments provided dense temporal coverage and sub-100 m s⁻¹ precision, enabling the system to be modeled across a full orbital cycle. When phased to the 5.0038-day period identified in the *TESS* photometry, the combined RVs revealed a coherent sinusoidal signal with a semi-amplitude consistent with a Jupiter-mass companion. This dynamical confirmation established TOI-640 b as a genuine short-period hot Jupiter. A spectrum obtained by HARPS (and partially reduced by the ADP pipeline) is shown in Figure 2.7.

In addition to the planetary signal, the radial-velocity data also showed a long-term trend incompatible with the orbital period of planet b. This slow acceleration suggested the presence of an additional outer companion, later confirmed as a long-period Jovian planet (TOI-640 c). The simultaneous detection of both RV components demonstrated that the TOI-640 system is dynamically complex and that its architecture includes at least two giant planets.

The Rossiter–McLaughlin (RM) effect provides one of the clearest spectroscopic diagnostics of spin–orbit geometry in transiting systems. See section 1.3.1 for more description. In TOI-640, Knudstrup et al. (2023) measured a pronounced

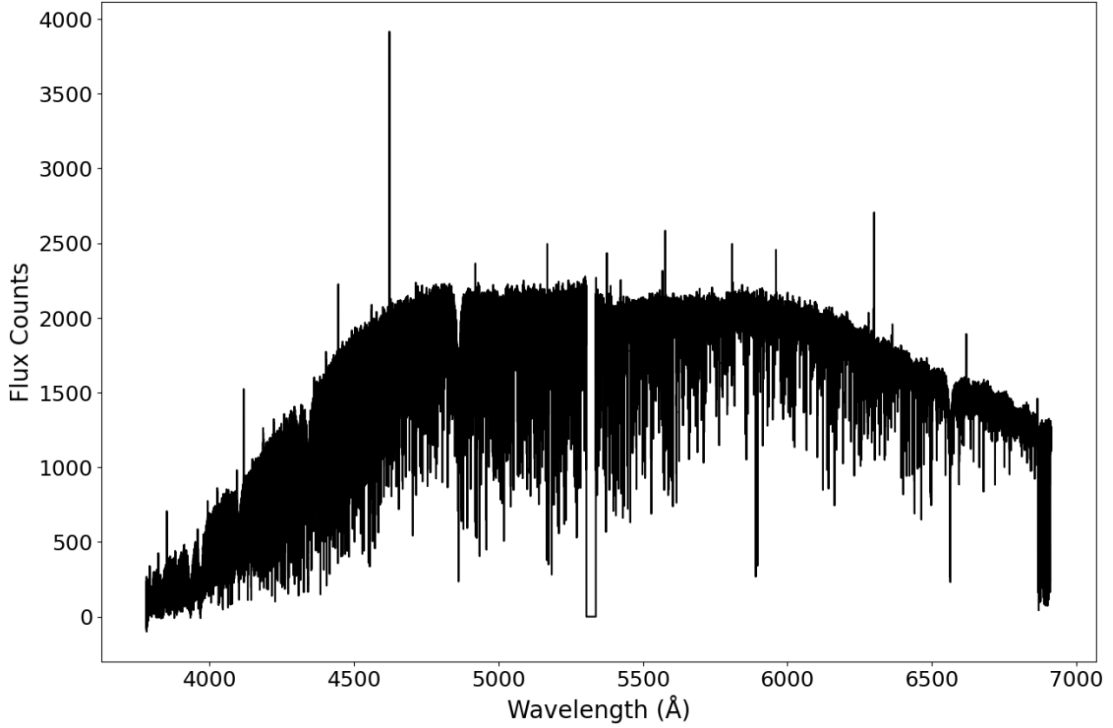


Figure 2.7: Full spectrum of TOI 640, as obtained by HARPS.

RM waveform with HARPS and showed that its shape is consistent with a highly misaligned, nearly polar orbit (Figure 2.8). This effect will become important later in the thesis because the same transit-coupled distortions of stellar line profiles that make the RM signal measurable can also imprint residual structure in transmission spectra, especially in strong stellar lines, and can therefore masquerade as or modify apparent planetary absorption features.

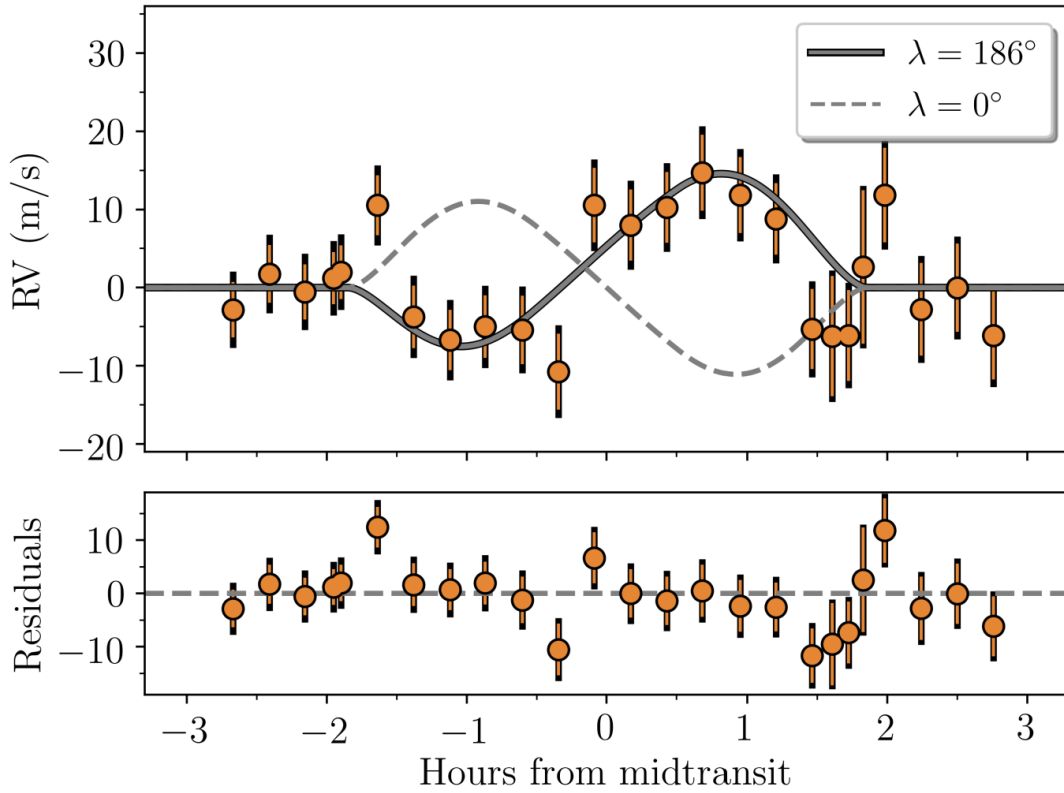


Figure 2.8: Rossiter-McLaughlin signal of TOI-640b measured with HARPS during transit. The shape of the signal is consistent with a strongly misaligned, nearly polar orbit. Adapted from Knudstrup et al. (2023, their Fig. 1).

Chapter 3

Description of Data and Analysis

The objective of this analysis is to search for atmospheric absorption by neutral hydrogen and sodium in the atmosphere of TOI 1288b and TOI 640b. This is accomplished by comparing spectra taken during planetary transit with spectra obtained outside of transit, thereby isolating wavelength-dependent signals attributable to the planetary atmosphere, the so-called transmission spectrum.

3.1 Temporal Organization

In order to generate transmission spectra from the two planets, FITS files were acquired from the ESO database. For TOI 640, 22 individual spectra from 2022 February 25 were downloaded from the ESO database. Data for TOI 1288 was taken on 2020 July 21. 9 individual spectra (in FITS format) were gathered from the same database.

The exposure time was extracted from the FITS files and converted to a uniform time standard using `astropy.time`. We used the TAPIR exoplanet transit finder (Swarthmore College Astronomy Department 2026) to cross-reference the observation times of each exposure with the expected transit time to determine which exposures occurred during- versus out-of-transit. To minimize systematic errors arising from Earth’s atmosphere, instrumental variation, and barycentric radial velocity, data was restricted to observations from a single night, ensur-

ing that any detected signal arises from the presence of the planetary atmosphere rather than other kinds of variation. For TOI 1288, four were considered in-transit, three were out, and two were discarded for straddling the ingress/egress points. Out of the 22 exposures of TOI 640, 14 were in-transit and 8 were out. Using the BATMAN (BAsic Transit Model cAlculationN) package (Kreidberg 2015), we input the system parameters from Knudstrup et al. (2022, 2023); Polanski et al. (2024) to create a flux versus time plot for each transit. Figure 3.1 shows each individual exposure in a different color, mapped onto the transit plot of the given system. Note that the shapes produced by BATMAN reflect the real shapes of the transit in a direct comparison to Figure 2.1. The shapes of transit flux curves differ between systems because different systems occult their host stars in different geometries and against different stellar brightness profiles. The transit depth is set primarily by the planet-to-star area ratio, while the total duration and the relative lengths of ingress and egress depend on the orbital geometry, especially the impact parameter and the planet’s projected velocity across the stellar disk. Limb darkening also changes the detailed curvature of the light curve, so two transits with similar depths can still have noticeably different profiles if the host stars or transit chords differ (Mandel & Agol 2002; Winn 2010).

3.2 TOI 1288

After sorting in-transit from out-of-transit exposures, we began with reproducing a non-detection of both $H\alpha$ and sodium in TOI 1288b as seen in Gonzales Quevedo (2024), developing and evaluating the validity of a transmission spectroscopy analysis pipeline.

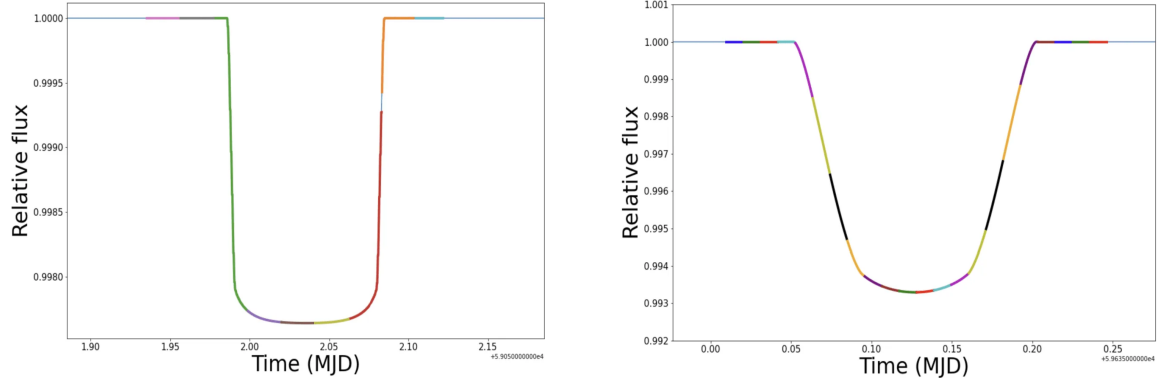


Figure 3.1: *Left:* TOI 1288 flux versus time during transit. *Right:* TOI 640 transit plot. Colored bars mapped to the transit profile show the individual exposures used for this project.

3.2.1 Extraction

The HARPS-N spectra are retrieved from the pipeline-reduced `e2ds` files (order-by-order extracted spectra). In this echelle spectrum, the detector gives flux versus pixel number for each order; in order to convert this into a physical wavelength, the pipeline stores a wavelength calibration solution in the header. The wavelength solution maps pixel index to a wavelength λ for each order. Because the dispersion is smooth within each order, this is approximated with a low-order polynomial. In this case, four coefficients correspond to one echelle order, and thus the polynomial for each order is composed of four unique terms, encoded in the header. The wavelength scale for each order is reconstructed by evaluating this polynomial across the detector pixels in that order.

At this stage, analysis focuses on the orders which were empirically identified as those containing $H\alpha$ and the sodium doublet. The extracted orders are trimmed to the wavelength subranges surrounding $H\alpha$ and sodium, thereby avoiding the noisier edges of the orders (Figure 3.2).

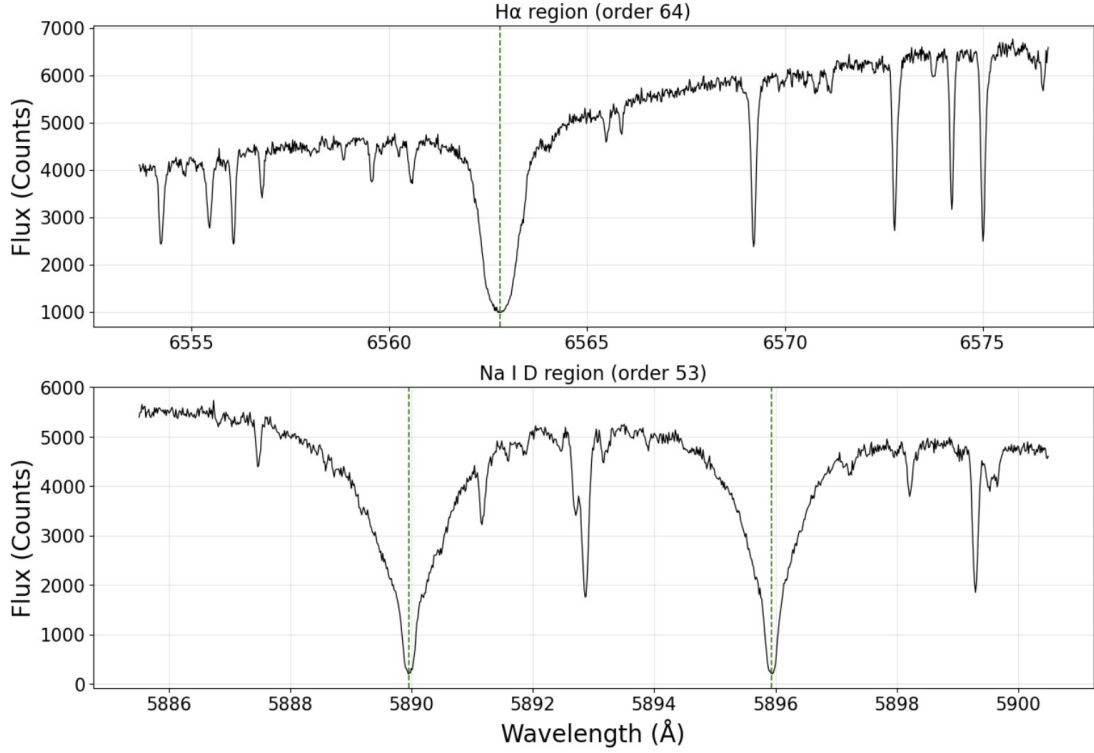


Figure 3.2: The raw spectrum surrounding $H\alpha$ and the sodium doublet in the stellar spectrum of TOI 1288.

3.2.2 Continuum Normalization

Continuum normalization is critical for high-resolution transit spectroscopy: small errors in normalization can produce spurious results when spectra are later combined, divided, or subtracted. To this end, our code implements multiple normalization attempts which progressively refine the continuum estimate by alternating between polynomial fits and sigma clips.

The following steps are shown in figures 3.3 and 3.4. First, a low-order (linear) polynomial is implemented to remove the dominant slope across the order segment, producing an intermediate normalized spectrum more suitable for identifying outliers.

After this, several refinement attempts are explored and fitted together for a

robustly normalized transmission spectrum. We sigma-clipped the preliminarily normalized spectrum, and then fit a high-order (11th) polynomial to the retained points. Then, a second clipping pass was performed to further exclude remaining artifacts and stellar features, followed by a moderate-order (5th) polynomial. Finally, we performed a clip based on the residuals from the continuum fit, where the most recent polynomial was compared to the original, raw spectrum. This approach effectively targets deviations in the flux and can be more stable near stronger absorption lines. So, in practice, the final normalization used for subsequent steps is the spectrum divided by the final polynomial continuum model. Figures 3.3 and 3.4 offer a visualization of most of these steps, and the final normalized continuum around $H\alpha$ and the sodium doublet for TOI 1288.

Per-pixel uncertainties are approximated using Poisson counting statistics, $\sigma \approx \sqrt{F}$ (where F is the flux count on the pixel itself), and then propagated through the normalization by dividing by the same continuum model used for the flux. This results in normalized error arrays for each exposure, allowing statistically meaningful weighted coaddition and transmission-spectrum uncertainties later on.

3.2.3 Combining Multiple Exposures

The adopted method assigns each exposure a per-pixel weight:

$$w_i(\lambda) = \frac{1}{\sigma_i(\lambda)^2},$$

and computes the master spectrum as:

$$F_{\text{master}}(\lambda) = \frac{\sum_i w_i(\lambda) F_i(\lambda)}{\sum_i w_i(\lambda)}.$$

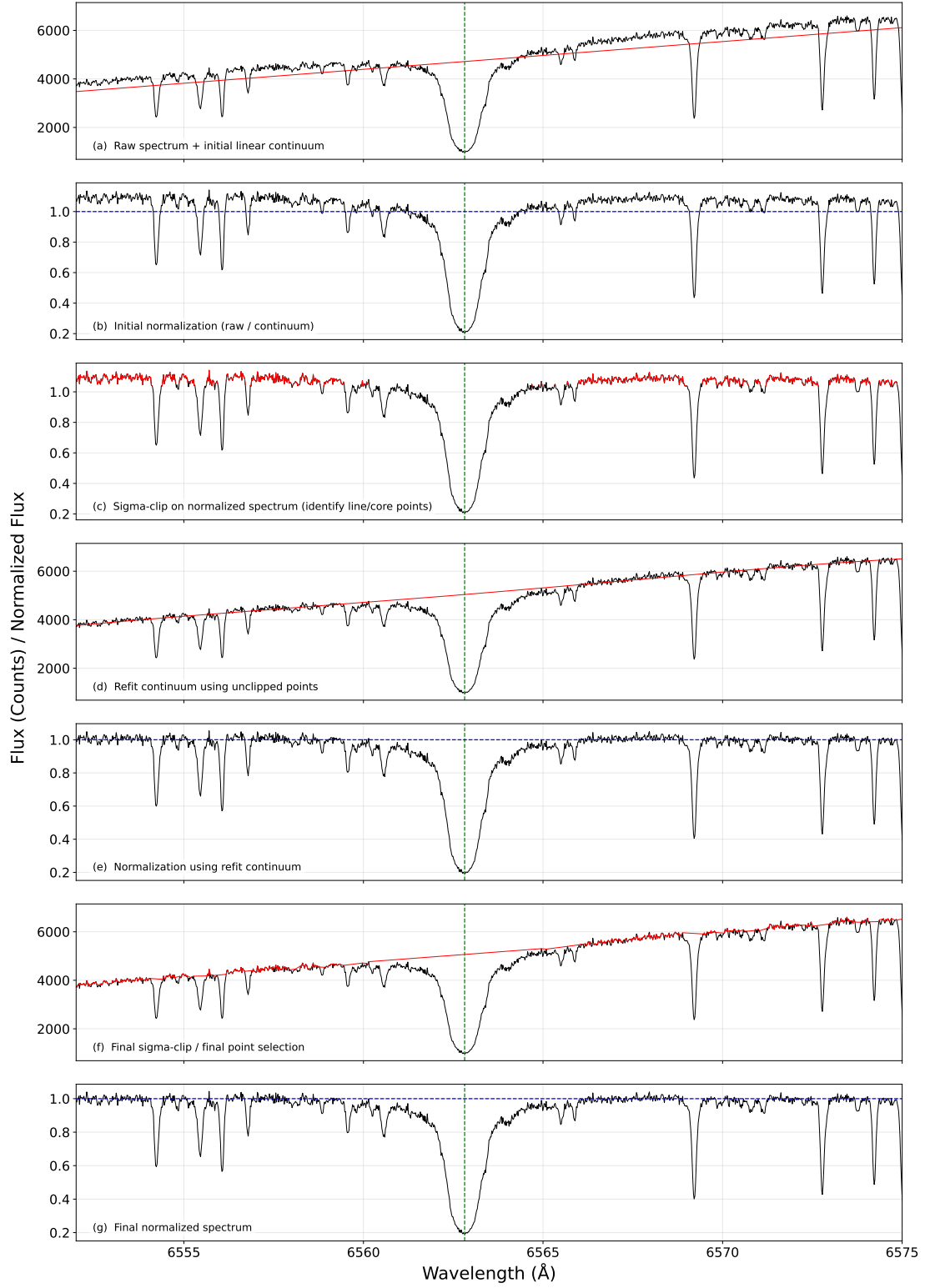


Figure 3.3: The TOI 1288 H α normalization pipeline.

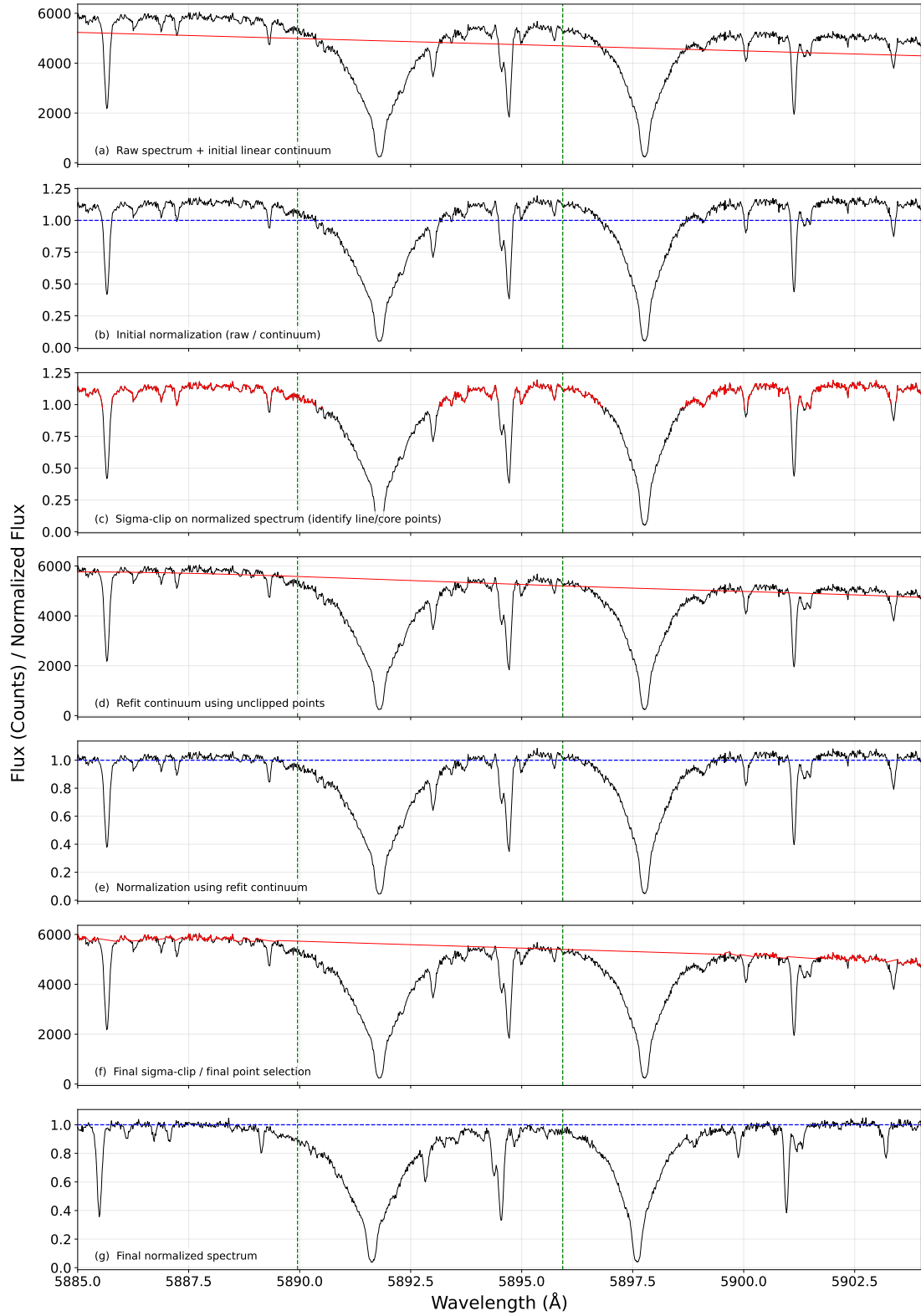


Figure 3.4: The TOI 1288 Na normalization pipeline.

Separate combined spectra are created for the in-transit and out-of-transit sets. This strategy maximizes sensitivity while down-weighting noisier exposures. Figure 3.5 shows each combined spectrum overlaid on the individual spectra that contribute to it.

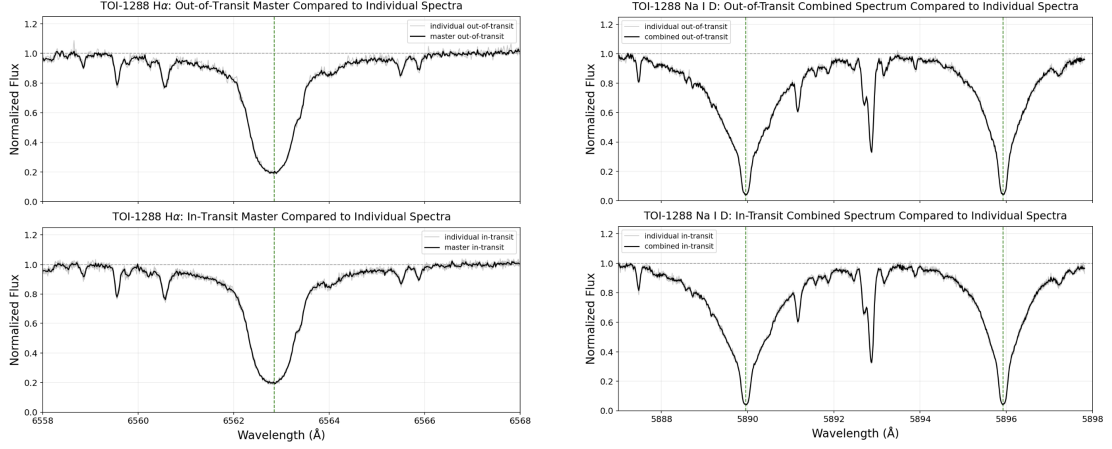


Figure 3.5: TOI 1288 combined spectra overlaid on top of the individual spectra which compose them.

3.2.4 Differential Transmission Around $H\alpha$ and the Sodium Doublet

With the combined in- and out-of-transit spectra, we compute a differential quantity of the form:

$$\delta(\lambda) = \frac{F_{\text{out}}(\lambda) - F_{\text{in}}(\lambda)}{F_{\text{out}}(\lambda)},$$

which is the standard transmission-spectroscopy diagnostic. This isolates any wavelength-dependent absorption present only during transit.

Uncertainties are propagated through weighted sum combination, weighted mean formation, and the final subtraction/division step.

Our binning routine computes inverse-variance weighted mean bins and assigns

each bin an uncertainty:

$$\sigma_{\text{bin}} = \left(\sum w \right)^{-1/2}$$

Figure 3.6 shows the transmission spectra for both species thus far.

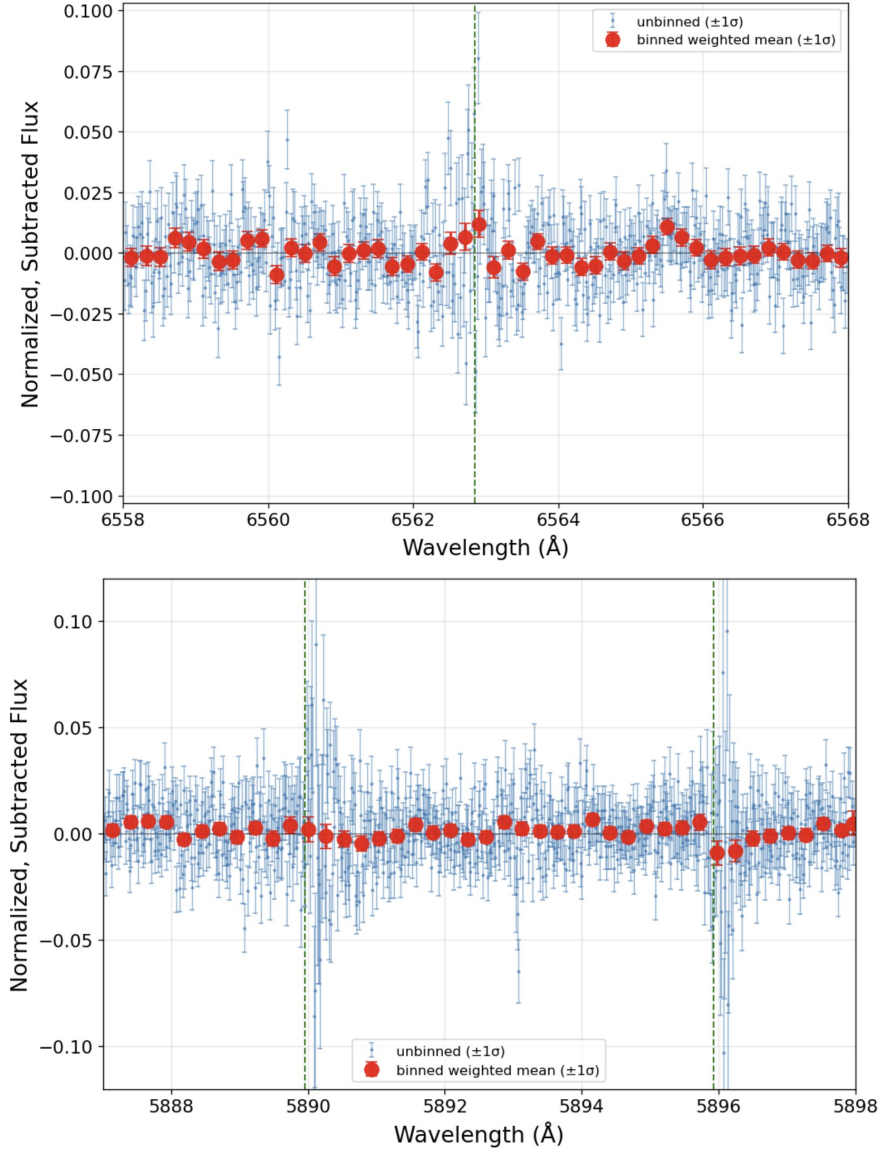


Figure 3.6: Top: TOI 1288 H α transmission spectrum thus far. Bottom: TOI 1288 Na transmission spectrum thus far.

3.3 TOI 640

The transmission spectrum analysis of TOI 640b followed the same general methodology as described previously for TOI 1288b, including the temporal separation of spectra, continuum normalization, inverse-variance weighted coaddition, and a resulting differential transmission spectrum. Only the differences in implementation and additional refinements specific to the TOI 640 dataset are described here.

The TOI-640b spectra were obtained in ADP (Advanced Data Product, partially pre-reduced by the European Southern Observatory pipeline) format and processed separately in the spectral regions surrounding both $H\alpha$ and the Na I doublet. Independent normalization and combination procedures were carried out for each spectral window.

3.3.1 Spectral Window Extraction and Normalization

For each ADP spectrum, wavelength and flux arrays were extracted from the FITS table extensions and cut to the wavelength intervals of interest. For the sodium analysis, a window spanning the Na I D doublet was selected, while a separate window centered on $H\alpha$ was used for hydrogen.

Continuum analysis followed the same general approach used for TOI 1288b; a low-order polynomial was first fitted to the extracted flux-wavelength segment and used to divide out the large-scale continuum slope. A sigma-clipping feature was used to remove strong absorption features and outliers before recomputing a refined polynomial fit. The raw spectrum was divided by this more refined model to normalize the spectrum with a continuum level at unity. Figures 3.7 and 3.8

show this normalization process.

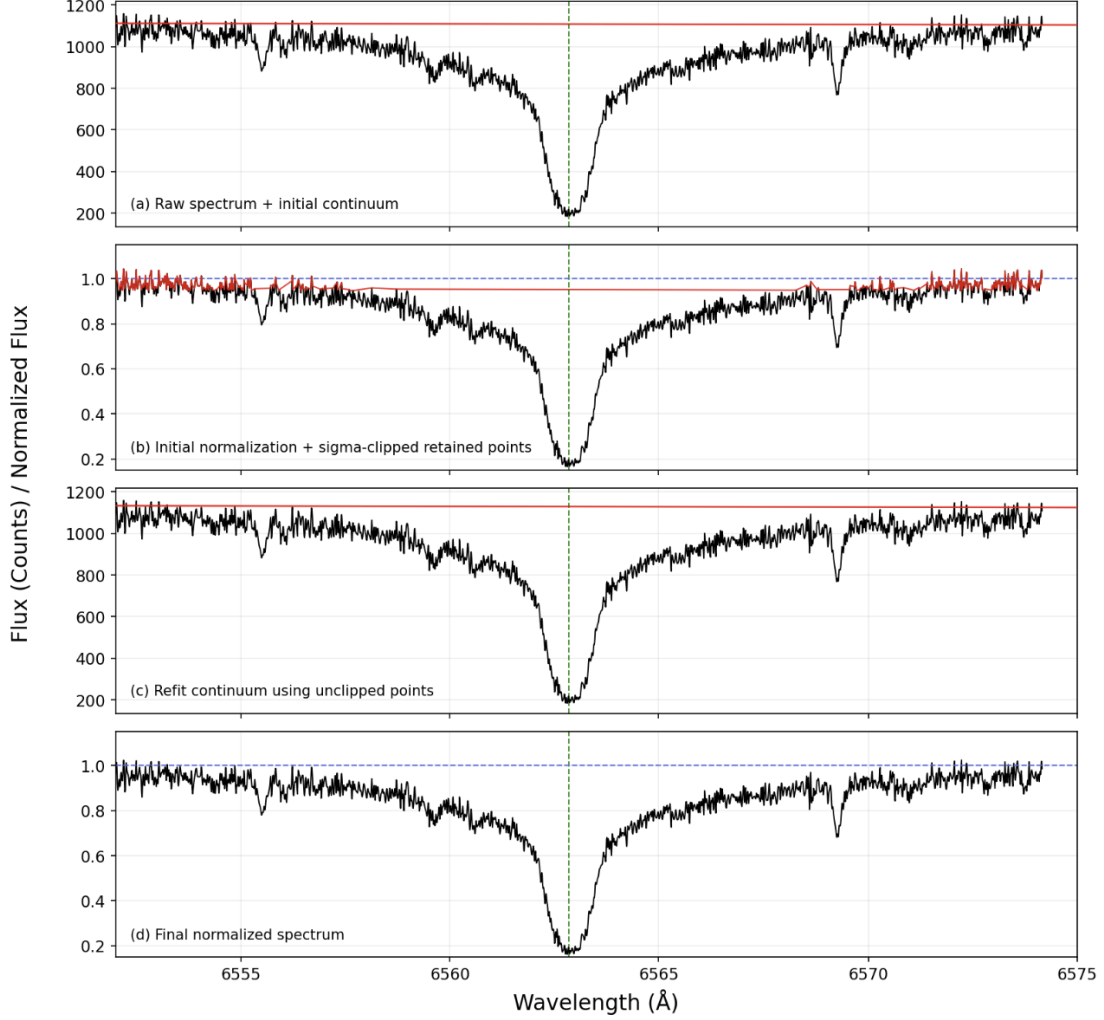


Figure 3.7: Normalization pipeline around $H\alpha$ for TOI 640. Note that the overall shape of the spectrum does not appear to change much; aside from a global slope which could be subtracted easily in a couple iterations, the ADP file was largely normalized already.

3.3.2 Wavelength Alignment Via Running Shift

In contrast to the simpler global shift approach used in the earlier TOI-1288b reduction, the TOI-640b analysis at first implemented a running (local) shift correction to mitigate small wavelength-dependent misalignments between spectra,

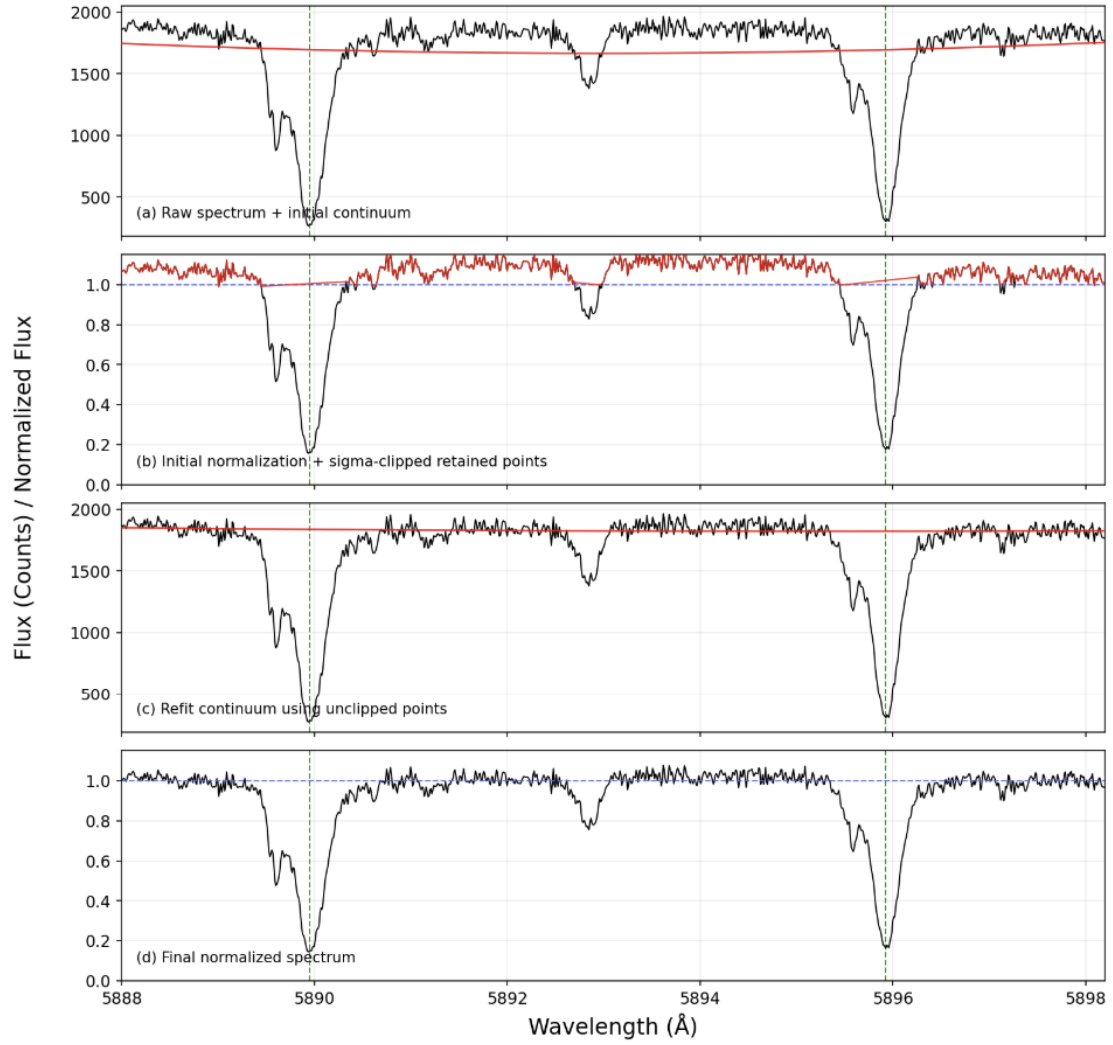


Figure 3.8: Normalization pipeline around the sodium doublet for TOI 640

though this later became redundant. This was originally inspired by Redfield et al. (2008), who noticed that small shifts appeared between different exposures that seemed to be a product of instrumental inconsistencies. The inclusion of the following is for clarity of the process.

A grid of trial wavelength shifts was applied to each spectrum over small overlapping wavelength chunks. For each chunk, the shift that minimized the residuals (via χ^2) was recorded. This produced a set of best-fit local shifts as a function of wavelength. These discrete shifts were then smoothed with a spline to construct a continuous shift map, which was applied on a per-pixel basis using spectral re-sampling (via `spectres`) before continuum normalization and combination. This procedure reduces “S-curve” residual artifacts caused by small distortions or calibration differences across orders. Figure 3.9 shows the process of going from an unshifted spectrum to one with the running shift applied.

3.3.3 Per-Exposure Error Estimates and Weighting

Per-pixel uncertainties were estimated using the square root of the flux counts and propagated through the continuum normalization using the same scaling as was applied to the flux. These normalized uncertainties were used to construct inverse-variance weights for each exposure.

As in the TOI-1288b analysis, master in-transit and out-of-transit spectra were produced using inverse-variance weighted means at each wavelength bin. This ensures that higher signal-to-noise exposures contribute proportionally more to the combined spectrum.

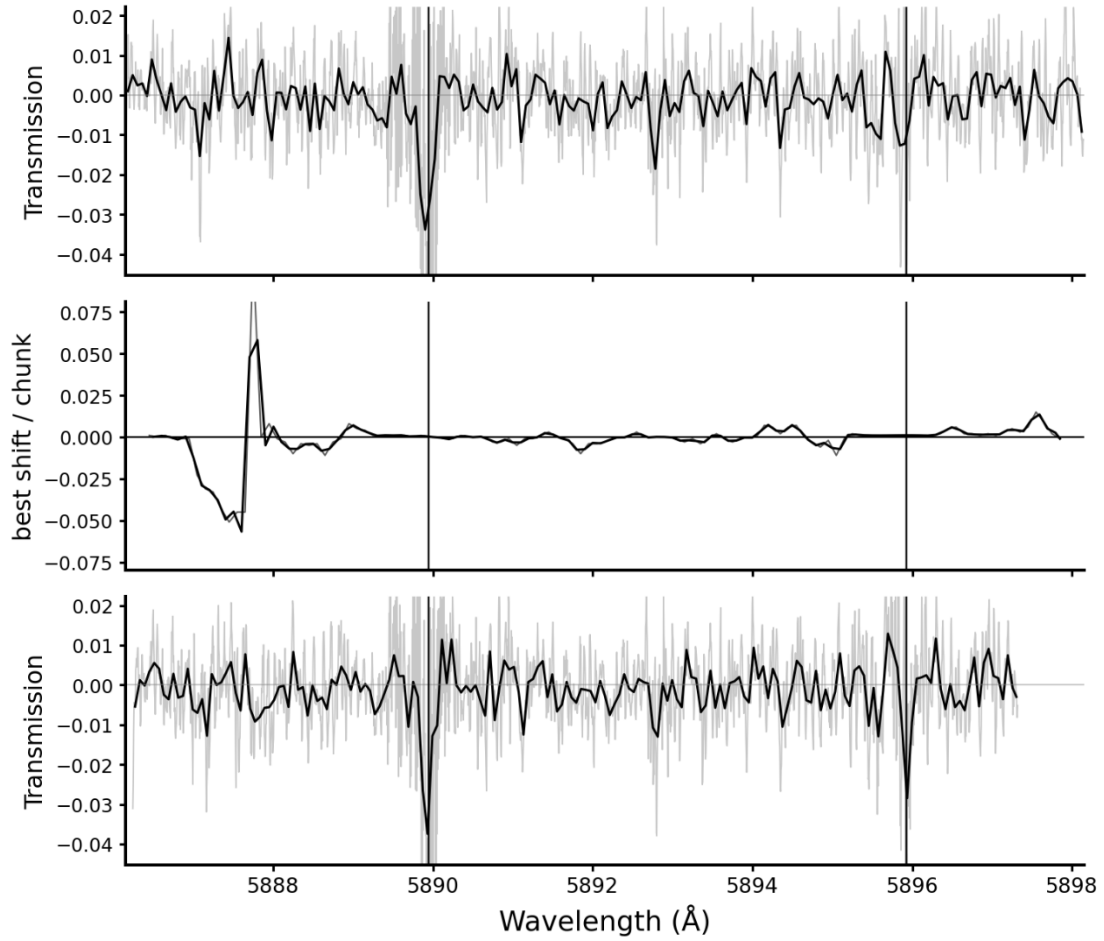


Figure 3.9: From top to bottom: the transmission spectrum before application of the running shift, the map showing the best shift per wavelength chunk (note that the map is very flat around the line values), and the transmission spectrum after that shift map has been applied. Note that both lines appear deeper.

3.3.4 Combined Spectrum and Transmission Spectra Construction

Weighted sums and total weights are computed separately for the in- and out-of-transit sets, producing combined normalized spectra for each group. A differential transmission spectrum was then constructed as before:

$$\delta(\lambda) = \frac{F_{\text{out}}(\lambda) - F_{\text{in}}(\lambda)}{F_{\text{out}}(\lambda)}$$

Uncertainties were propagated analytically from the weighted-mean errors of the master spectra, using standard error-propagation formulas for subtraction and division, consistent with the procedure described in the TOI-1288b section. Figure 3.10 shows the transmission spectra for both sodium and $\text{H}\alpha$ at this point in the reduction.

3.3.5 Tellurics

In order to confirm that the signals in our transmission spectra were not caused by absorption from Earth’s atmosphere, we obtained a `SkyCalc` model set to the time and location of our observations of TOI 640. To overlay this model onto our normalized spectra, we used the O_2 lines around 6890 Å to judge wavelength shift, and a series of lines at 6290-6300 Å to judge depth. Figure 3.11 shows our sequence of checks, ending with the model overplotted onto a single exposure. We take the lack of significant features overlapping our sodium lines as indicative of negligible telluric absorption in our region of interest. In addition, because all of our observations were taken on the same night (within the same few hours), it is unlikely that the telluric signature is different per exposure, and thus would tend

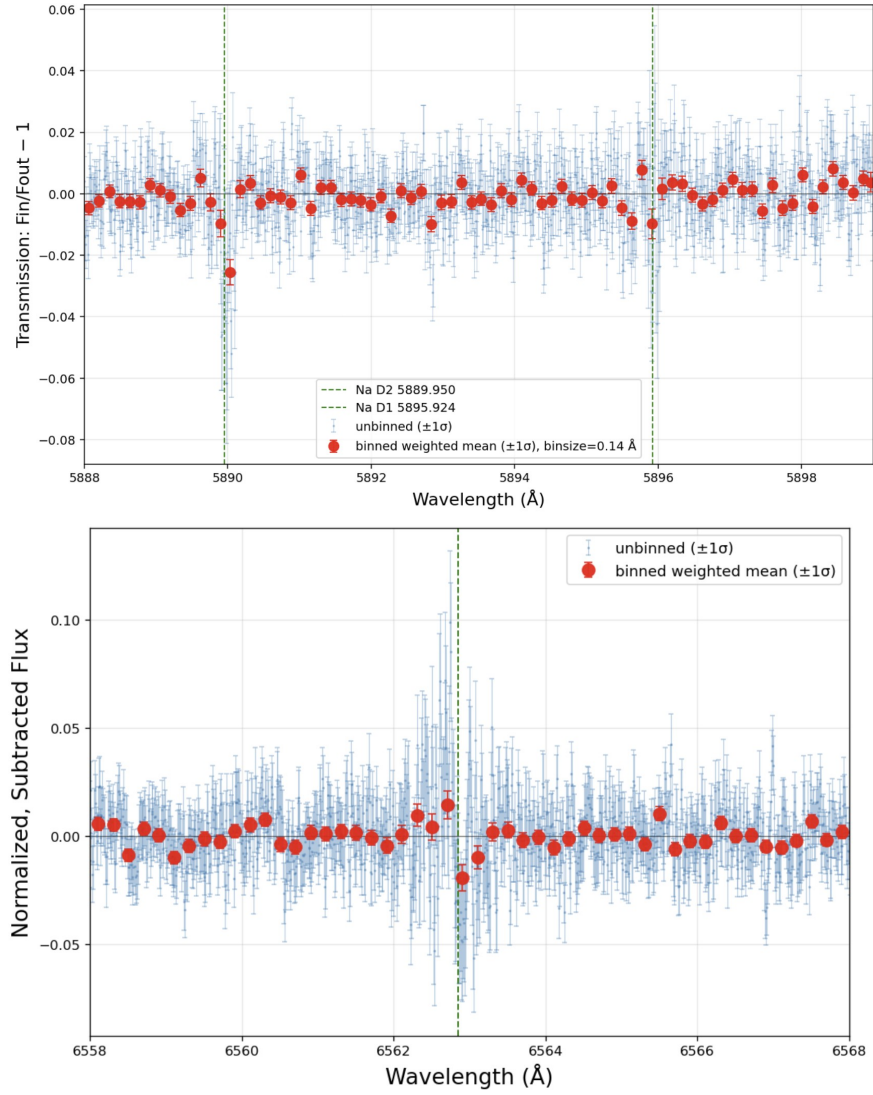


Figure 3.10: Top: TOI 640b Na transmission spectrum thus far. Bottom: H α transmission spectrum thus far.

to be subtracted out along with stellar features. This analysis is for redundancy.

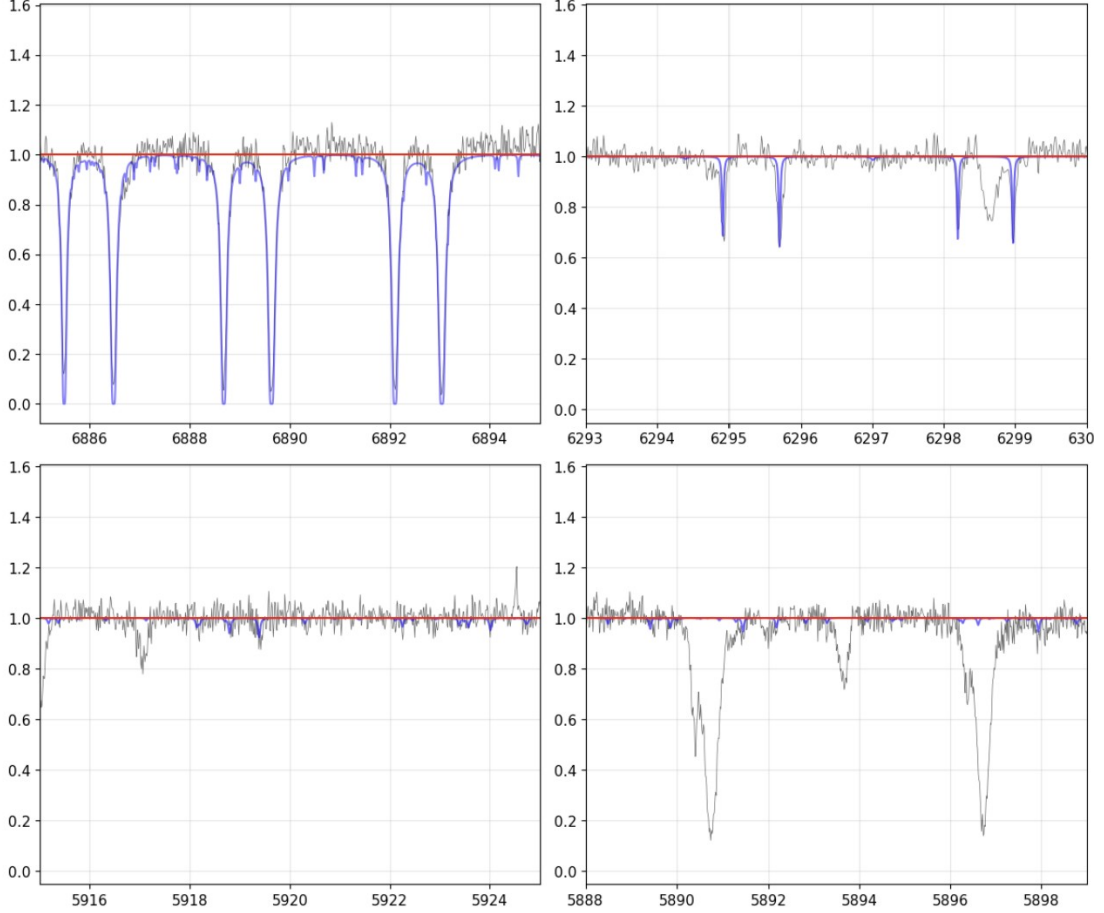


Figure 3.11: From left to right and top to bottom, our process for fitting the telluric model to our data. Wavelength shift, depth, an additional check, and the model overlaid on the sodium doublet.

3.3.6 Radial Velocity Shifting

In high-resolution transmission spectroscopy, the spectral features of the planetary atmosphere shift in wavelength throughout the transit due to the orbital motion of the planet. Although it is true that the radial velocity of the planet is 0 in the exact middle of transit, it can reach tens of km s^{-1} at ingress and egress, especially for planets orbiting very close to their star. To account for this motion

and avoid smearing the signal during coaddition, each exposure must be shifted into the planetary rest frame before combining the spectra.

The radial velocity of the planet at the midpoint of each exposure was calculated from the known orbital parameters of the system (Knudstrup et al. 2023; Polanski et al. 2024). Assuming a circular orbit, the instantaneous radial velocity of the planet can be written as

$$v_p(t) = K_p \sin\left(\frac{2\pi(t - T_0)}{P}\right),$$

where P is the orbital period, T_0 is the mid-transit time, and K_p is the radial velocity semi-amplitude of the planet. The semi-amplitude is related to the stellar radial velocity semi-amplitude $K_\star$ through the ratio of the stellar and planetary masses,

$$K_p = K_\star \frac{M_\star}{M_p}.$$

This relation follows from conservation of momentum in the two-body system, where the star and planet orbit their common center of mass. For each exposure, the timestamp recorded in the FITS header was converted into a uniform time system, and the midpoint of the exposure was used to evaluate the orbital phase. The corresponding planetary radial velocity was then computed using the above expression, shown in Figure 3.12.

Once the instantaneous planetary velocity was determined, the spectra were shifted into the planetary rest frame using the Doppler relation between velocity and wavelength. For non-relativistic velocities typical of exoplanet orbital motion, the wavelength shift is approximated by

$$\Delta\lambda = \lambda \frac{v_p}{c},$$

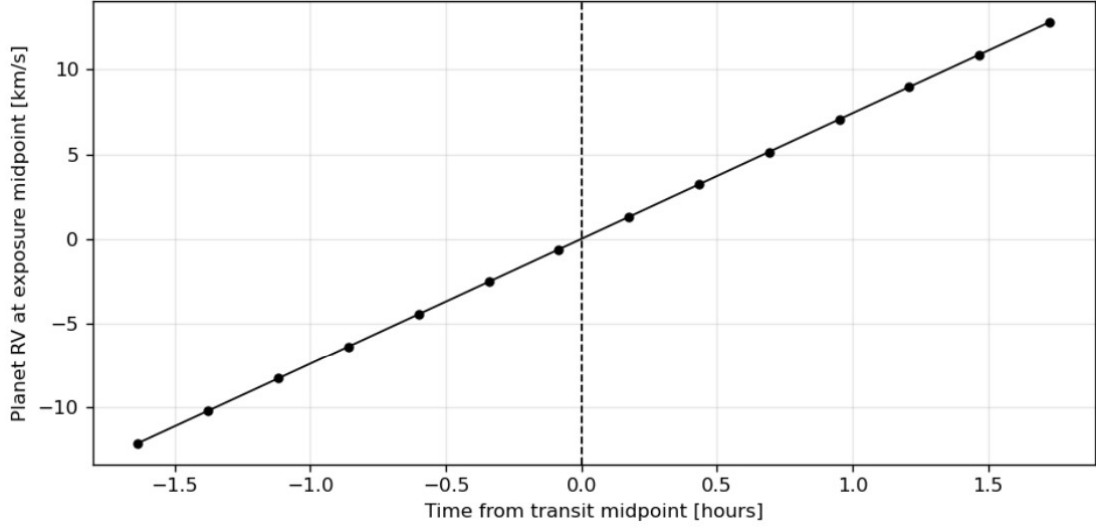


Figure 3.12: Planetary radial velocity at the midpoint of each in-transit exposure, shown as dots.

where c is the speed of light and λ is the wavelength of the spectral bin. Each exposure was therefore resampled onto a wavelength grid shifted by this amount, effectively aligning the expected planetary absorption features across all spectra.

This procedure ensures that absorption features originating in the planetary atmosphere remain fixed in wavelength during the coaddition process, while stellar and telluric residuals, which do not share the same velocity evolution, tend to average out. The aligned spectra were then combined using the inverse-variance weighted coaddition method described previously to construct the final transmission spectrum, shown and discussed in Chapter 4. In the end, shifting each exposure using its individual radial velocity eliminated in large part the s-curves that we had sought to address through the running shift method, rendering that step unnecessary.

Chapter 4

Results: Atomic Transmission Spectra of TOI-1288b and TOI-640b

4.1 Chapter Overview

This chapter presents the final transmission spectra produced in this work for TOI-1288b and TOI-640b in the $H\alpha$ and Na I doublet regions. The results are reported as (i) final, planet-rest-frame transmission spectra and (ii) quantitative line measurements or upper limits derived from those spectra. The principal result is a statistically significant Na I detection in TOI-640b at an integrated significance of $\sim 4.8\sigma$ (Section 4.3.2), with control-line and robustness checks including a Ca I 8500 Å control analysis (Section 4.3.3) and comparison to a forward model generated using `petitRADTRANS` (Section 4.3.5). The remaining measurements are non-detections: TOI-1288b shows no statistically significant absorption in either $H\alpha$ or Na I (Section 4.2), and TOI-640b shows no statistically significant $H\alpha$ absorption (Section 4.3.1).

4.2 TOI-1288b: Final Transmission Spectra

4.2.1 $H\alpha$ (Non-Detection)

The final TOI-1288b $H\alpha$ transmission spectrum is consistent with zero excess absorption across the line core within the propagated uncertainties. No coherent absorption feature is present at the $H\alpha$ rest wavelength in either the unbinned spectrum or the weighted-binned spectrum. This result is reported here as a non-detection (see Figure 4.1).

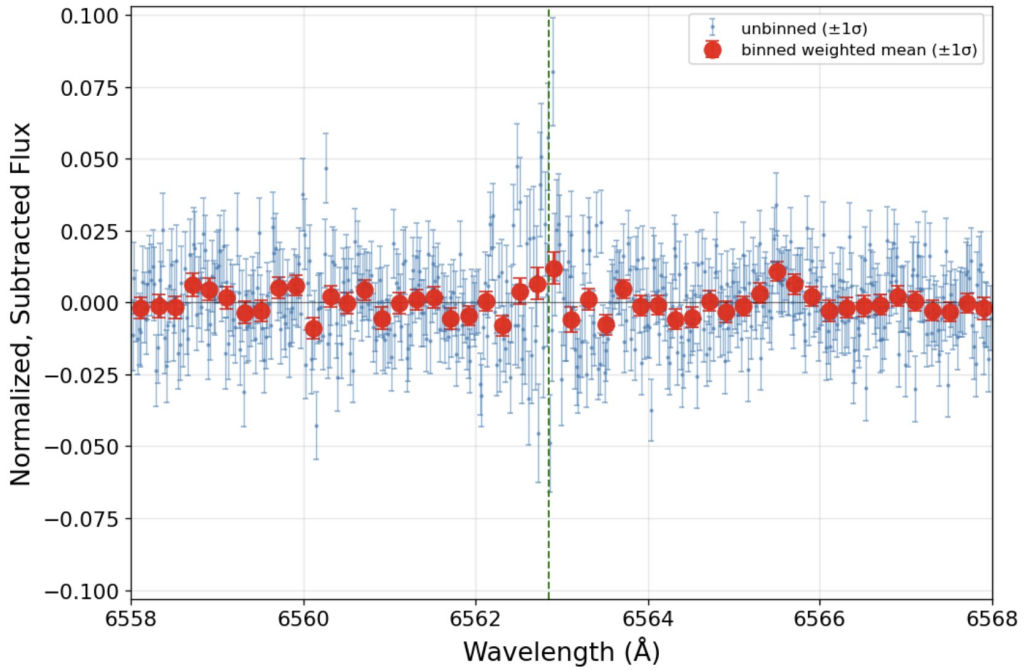


Figure 4.1: Final TOI-1288b $H\alpha$ transmission spectrum (planet rest frame), shown unbinned with propagated uncertainties and as a weighted-binned spectrum. The spectrum is consistent with zero excess absorption across the $H\alpha$ core.

4.2.2 Na I D Doublet (Non-Detection)

The final TOI-1288b Na I transmission spectrum (D_2 and D_1 region) shows no statistically significant absorption at either doublet component. The unbinned and weighted-binned spectra are consistent with zero within the uncertainties, and this is reported as a non-detection of Na I in TOI-1288b (see Figure 4.2).

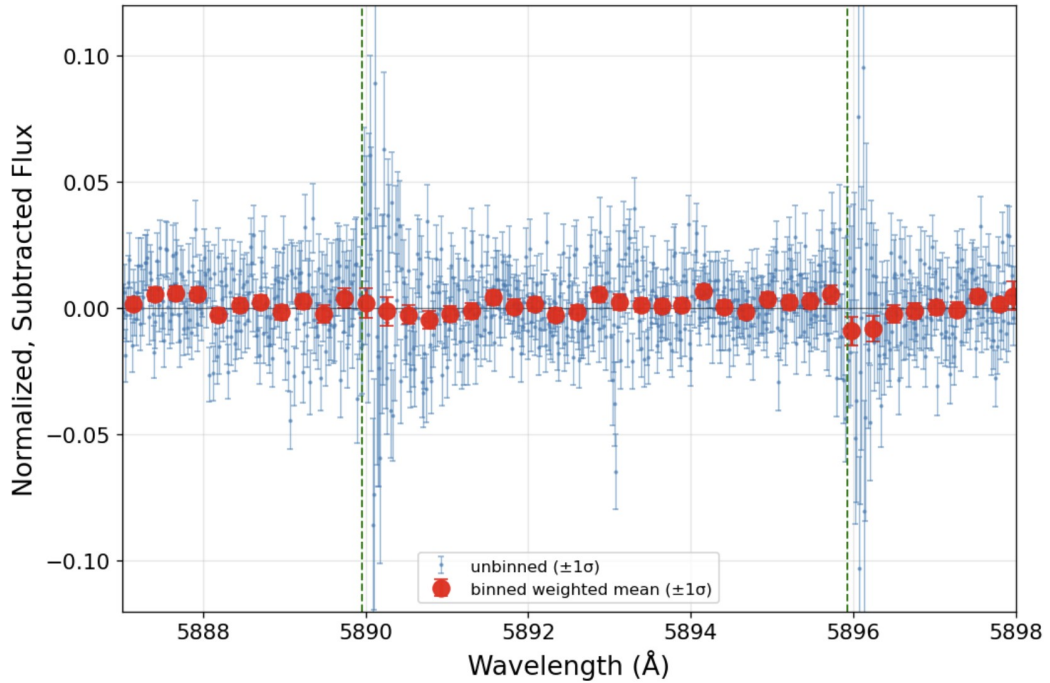


Figure 4.2: Final TOI-1288b Na I transmission spectrum (planet rest frame), shown unbinned with propagated uncertainties and as a weighted-binned spectrum across the Na D doublet. No statistically significant absorption is detected at either line.

4.3 TOI-640b: Final Transmission Spectra

4.3.1 $H\alpha$ (Non-Detection)

The final TOI-640b $H\alpha$ transmission spectrum is consistent with zero excess absorption across the line core within the propagated uncertainties. No coherent

absorption signature is present at the $H\alpha$ rest wavelength in the unbinned spectrum, and the weighted-binned spectrum remains consistent with zero. This is reported as a non-detection of $H\alpha$ absorption in TOI-640b (see Figure 4.3).

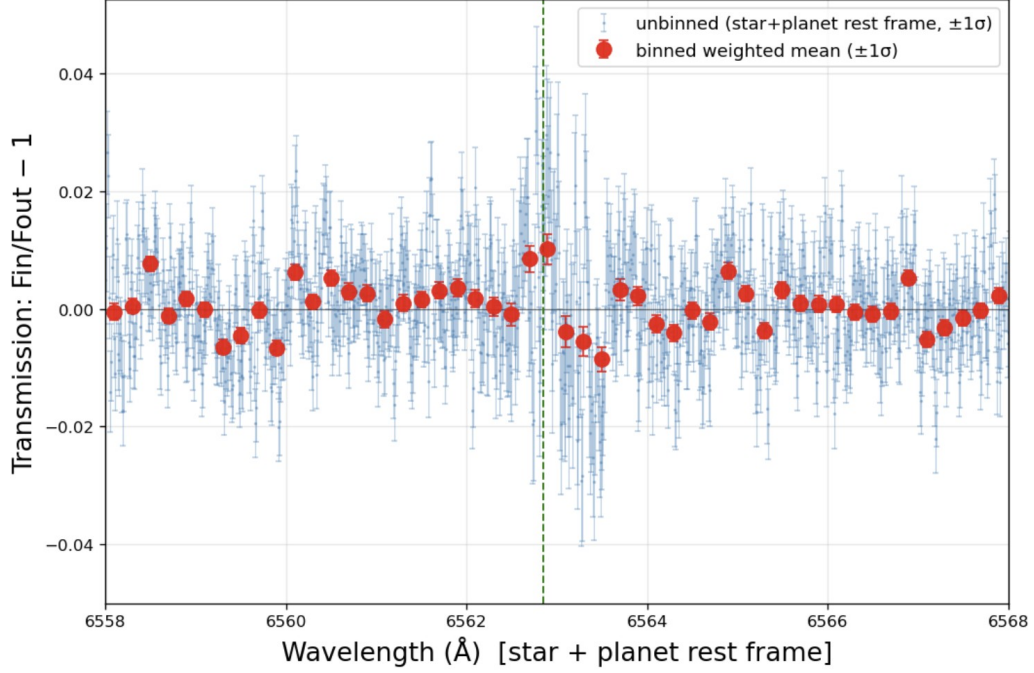


Figure 4.3: Final TOI-640b $H\alpha$ transmission spectrum (planet rest frame), shown unbinned with propagated uncertainties and as a weighted-binned spectrum. The spectrum is consistent with zero excess absorption across the $H\alpha$ core.

4.3.2 Na I D Doublet (Detection)

The final TOI-640b Na I transmission spectrum exhibits statistically significant excess absorption in the vicinity of the Na D doublet (see Figure 4.4). Quantitative measurements were performed for each line individually (D_2 and D_1) and for the combined doublet. Results are reported both as a weighted-mean depth statistic in the line core and as an integrated (equivalent-width-like) statistic within fixed passbands, with propagated uncertainties.

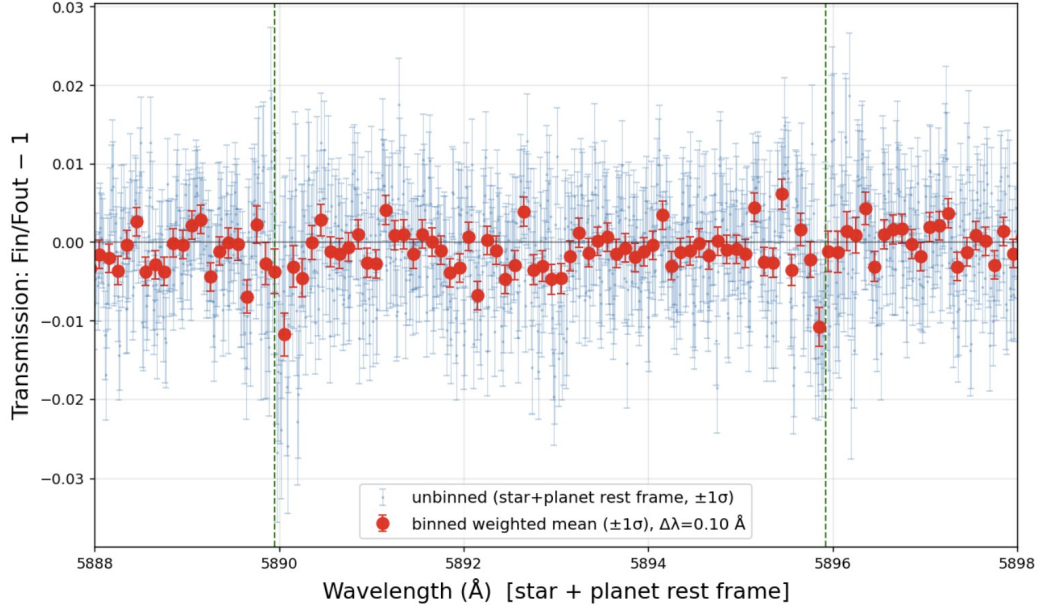


Figure 4.4: Final TOI-640b NaI transmission spectrum (planet rest frame), shown unbinned with propagated uncertainties and as a weighted-binned spectrum across the Na D doublet. A significant absorption feature is detected, dominated by the D₂ line.

Line-by-line Significance Measurements

For the Na D₂ line, the measured weighted-mean depth is

$$\langle \delta \rangle_{D_2} = -0.00393 \pm 0.00090,$$

corresponding to a mean-depth significance of -4.3σ . For the Na D₁ line, the measured weighted-mean depth is

$$\langle \delta \rangle_{D_1} = -0.00204 \pm 0.00085,$$

corresponding to a mean-depth significance of -2.4σ . A combined doublet weighted-mean metric yields an overall significance of approximately -4.7σ .

Integrated absorption measurements (computed separately for D₂ and D₁ pass-

bands and combined by summing the two integrals and adding uncertainties in quadrature) yield integrated significances of $\sim 4.4\sigma$ (D_2), $\sim 2.3\sigma$ (D_1), and a combined integrated significance of $\sim 4.8\sigma$ for the Na doublet. The combined integrated significance is therefore reported as the headline detection strength for Na in TOI-640b (see Table 4.1 for the compilation of measurements).

Table 4.1: Measured Na I absorption in TOI-640b from the final transmission spectrum. Mean-depth values report the weighted-mean excess absorption in the line core, while integrated values report an equivalent-width-like statistic within fixed line passbands.

Feature	Mean depth	Mean-depth significance	Integrated significance
Na D_2	-0.003927 ± 0.000904	4.34σ	4.41σ
Na D_1	-0.002044 ± 0.000852	2.40σ	2.33σ
Na D_2+D_1 (combined)	—	4.73σ	4.8σ

4.3.3 Ca I 6162.17 Å Control-Line Check

To test whether the Na detection could plausibly arise from generic reduction artifacts rather than a species-specific atmospheric signal, an otherwise identical transmission-spectroscopy pipeline was applied to a nearby stellar control line: Ca I at 6162.17 Å. This control analysis produced no convincing planet-atmosphere absorption signature at the Ca line center in the planet rest frame, but did raise worry: localized residual structure is present near the stellar Ca line (consistent with incomplete removal of stellar line-profile variations and/or correlated normalization/registration residuals). This structure reaches a significance of $\sim 3.5\sigma$. The result (See Figure 4.5) is reported as a non-detection of planetary Ca absorption, but its implications are further analyzed in Chapter 5.

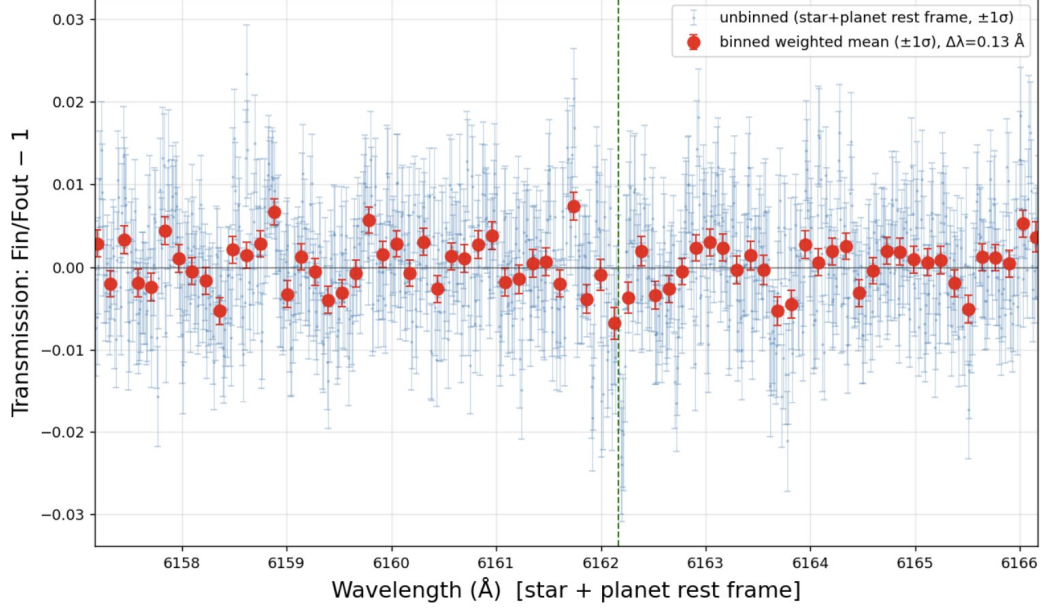


Figure 4.5: TOI-640b CaI 6162.17 Å control-line transmission spectrum processed with the same analysis pipeline as the Na region. No convincing planet-atmosphere absorption feature is detected at line center; residual structure is interpreted as stellar/analysis residuals.

4.3.4 Detection Significance for the Sodium Doublet and the Calcium Control Line

After constructing the final transmission spectrum,

$$\delta(\lambda) \equiv \frac{F_{\text{in}}(\lambda)}{F_{\text{out}}(\lambda)} - 1, \quad (4.1)$$

with associated propagated 1σ uncertainty $\sigma(\lambda)$, the significance of any line-centered absorption feature was quantified in two complementary ways: (i) a weighted mean depth measured in a small passband centered on the line, and (ii) an integrated, equivalent-width-like signal measured over the same interval. This is the same basic philosophy commonly adopted in high-resolution sodium transmission studies, where narrow windows around the Na I D lines are used to

quantify line-resolved atmospheric absorption (Wytenbach et al. 2015).

Weighted-Mean Line Depth

For a given line centered at λ_0 , a symmetric passband

$$\lambda_0 - \Delta\lambda_{\text{line}} \leq \lambda \leq \lambda_0 + \Delta\lambda_{\text{line}} \quad (4.2)$$

was selected. If the spectrum within that window contains N samples $\delta_i \equiv \delta(\lambda_i)$ with uncertainties $\sigma_i \equiv \sigma(\lambda_i)$, inverse-variance weights

$$w_i = \frac{1}{\sigma_i^2} \quad (4.3)$$

were assigned to each point. The weighted mean line depth was then computed as

$$\bar{\delta} = \frac{\sum_{i=1}^N w_i \delta_i}{\sum_{i=1}^N w_i}, \quad (4.4)$$

with formal uncertainty

$$\sigma_{\bar{\delta}} = \left(\sum_{i=1}^N w_i \right)^{-1/2}. \quad (4.5)$$

The corresponding mean-depth detection significance is therefore

$$S_{\text{mean}} = \frac{\bar{\delta}}{\sigma_{\bar{\delta}}}. \quad (4.6)$$

Because the transmission spectrum is defined as $F_{\text{in}}/F_{\text{out}} - 1$, an absorption line appears as $\bar{\delta} < 0$. In practice, the magnitude $|S_{\text{mean}}|$ is quoted as the formal detection significance, while the sign preserves the physical sense of the signal.

Integrated Line Signal

A second metric was obtained by integrating the transmission spectrum across the same passband. Since absorption corresponds to negative $\delta(\lambda)$, the integrated line strength was defined as

$$W_{\text{line}} = - \int_{\lambda_0 - \Delta\lambda_{\text{line}}}^{\lambda_0 + \Delta\lambda_{\text{line}}} \delta(\lambda) d\lambda, \quad (4.7)$$

which is an equivalent-width-like quantity with units of wavelength. In the discrete spectrum this was evaluated numerically over the samples in the chosen passband. The uncertainty on the integrated signal was propagated from the per-pixel uncertainties as

$$\sigma_W^2 = \sum_{i=1}^N [\sigma_i \Delta\lambda_i]^2, \quad (4.8)$$

where $\Delta\lambda_i$ is the effective wavelength width associated with sample i (for example, the local trapezoidal or midpoint spacing). The integrated detection significance was then defined as

$$S_{\text{int}} = \frac{W_{\text{line}}}{\sigma_W}. \quad (4.9)$$

Sodium Doublet: D₂, D₁, and the Combined Doublet

For sodium, the procedure above was applied separately to the D₂ and D₁ lines, centered at the corrected doublet wavelengths. The line-by-line treatment is well motivated, because high-resolution sodium transmission spectroscopy typically resolves the two components of the doublet and measures their depths independently (Wytttenbach et al. 2015). Thus, for each of D₂ and D₁, Eqs. 4.4–4.9 were evaluated independently.

A combined sodium significance was then formed from the two line windows.

For the weighted-mean metric, the combined passband was simply the union of the D_2 and D_1 samples, so that Eqs. 4.4–4.6 were evaluated over both windows together. For the integrated metric, however, the two line windows must be handled separately and only combined afterwards. Because the D_2 and D_1 windows are disjoint, integrating both windows at once with a single trapezoidal call would erroneously connect the end of one line window to the start of the other and artificially add the large continuum gap between the two lines. The correct combined integrated signal is therefore

$$W_{\text{Na,tot}} = W_{D2} + W_{D1}, \quad (4.10)$$

with uncertainty

$$\sigma_{W,\text{Na,tot}} = \sqrt{\sigma_{W,D2}^2 + \sigma_{W,D1}^2}, \quad (4.11)$$

and combined integrated significance

$$S_{\text{int,Na}} = \frac{W_{\text{Na,tot}}}{\sigma_{W,\text{Na,tot}}}. \quad (4.12)$$

Calcium Control Line

The calcium analysis used exactly the same formalism as the sodium analysis, but applied to a single control line rather than to a resolved doublet. The weighted-mean depth and integrated significance were therefore computed directly from Eqs. 4.4–4.9. In this case, the purpose of the measurement was not primarily to claim a calcium detection, but to assess whether the full transmission-spectrum pipeline generated spurious line-centered residuals in a strong stellar line. This is an important control because line-centered transmission spectra are known to

be vulnerable to stellar contamination, especially center-to-limb variation (CLV) and the Rossiter–McLaughlin (RM) effect, which can imprint or distort apparent absorption signatures even when no planetary signal is present (Yan et al. 2017; Reiners et al. 2023).

Local Sideband RMS as an Empirical Sanity Check

In addition to the formal propagated uncertainties, a local empirical noise estimate was computed from sidebands bracketing each line window. If the sidebands are defined as regions sufficiently near the line to sample the same local noise properties, but far enough away to avoid the line core itself, then the sideband root-mean-square

$$\text{RMS}_{\text{side}} = \sqrt{\frac{1}{M-1} \sum_{j=1}^M [\delta(\lambda_j) - \langle \delta \rangle_{\text{side}}]^2} \quad (4.13)$$

provides a useful empirical consistency check on the formal line significance. For the TOI 640 data, the sideband noise significance across the spectrum hovered at $\sim 1.4\sigma$. Agreement between the propagated line-window uncertainties and the sideband RMS supports the interpretation that the quoted detection significance is not being driven by a single pathological bin or by an obviously poorly estimated noise model.

4.3.5 Forward-Model Comparison with `petitRADTRANS`

A forward model transmission spectrum in the Na region was generated using `petitRADTRANS`, a publicly available radiative-transfer package designed for exoplanet spectral characterization and retrieval (Mollière et al. 2019). `petitRADTRANS`

is optimized to generate both transmission and emission spectra quickly, using a “correlated-k” treatment at low resolution and a line-by-line treatment at high resolution. It also includes gas and cloud opacities appropriate for hydrogen-dominated exoplanet atmospheres, making it well suited for qualitative comparison between observed line profiles and physically plausible model atmospheres. The model spectrum was produced on an Å grid across the Na D doublet window and expressed in excess absorption relative to a local continuum for direct visual comparison to the observed transmission spectrum. This model is presented here as a qualitative reference for line shape and plausible absorption amplitude in a hydrogen-dominated hot-Jupiter atmosphere, and is not used for parameter inference in this Results chapter. The relative amplitudes of the individual lines in the model do not yet reflect the actual data; the “future work” section following the discussion and conclusion will review what remains to be done to use this model as a real analytical tool.

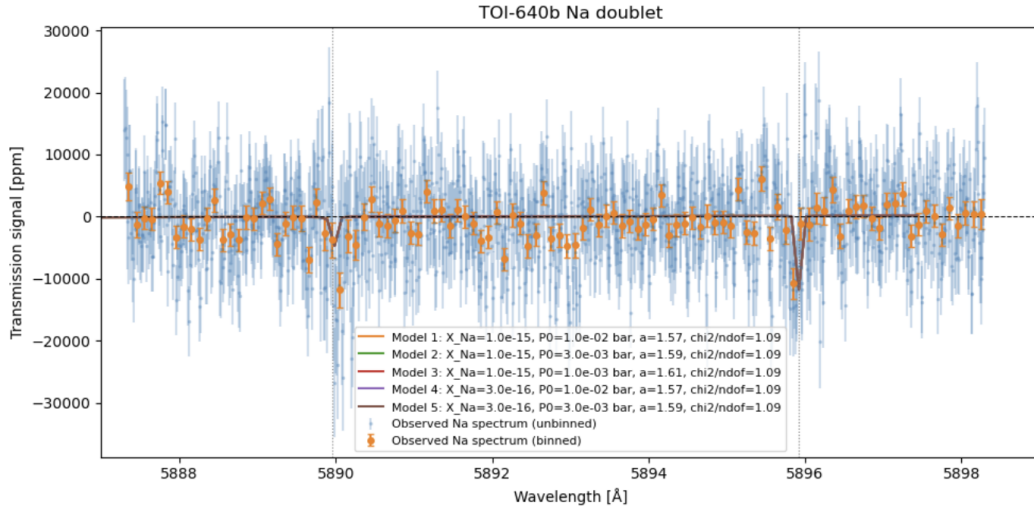


Figure 4.6: Observed TOI-640b Na transmission spectrum compared to an illustrative *petitRADTRANS* forward model (Mollière et al. 2019). The model is shown as a qualitative reference for line morphology and expected absorption scales in an exoplanetary atmosphere.

4.4 Summary of Results

The final transmission spectra produced in this work yield the following observational outcomes: (i) TOI-1288b shows no statistically significant absorption in either H α or Na I; (ii) TOI-640b shows no statistically significant H α absorption; (iii) TOI-640b exhibits a significant Na I detection, with a combined integrated significance of $\sim 4.8\sigma$, dominated by the D₂ component; and (iv) a Ca I 6162.17 Å control-line analysis yields no convincing planetary Ca detection, but remains to be analyzed as a caution to confidence.

Chapter 5

Discussion/Interpretation

5.1 Overview and Guiding Questions

This thesis was motivated by a deliberately narrow observational question with broad interpretive consequences: under what conditions are common optical tracers measurable in transmission spectra, and what do detections and non-detections imply about atmospheric structure, excitation, and observational systematics? Chapter 4 established three empirical outcomes. TOI-1288b shows no statistically significant absorption in either Na I or H α ; TOI-640b shows no statistically significant H α absorption; and TOI-640b exhibits a significant Na I detection with a combined integrated significance of $\sim 4.8\sigma$, dominated by the D₂ component. In this chapter, I interpret those outcomes in the context of prior Na and H α transmission studies and assess how the Ca I control-line behavior affects confidence in the Na detection.

A useful place to begin is with the fact that Na D and H α do not probe the same atmospheric layers. In transmission, sodium is generally interpreted as a tracer of the lower-to-middle atmosphere, at altitudes where Na remains neutral and where the line cores are not fully obscured by aerosols (Seager & Sasselov 2000; Madhusudhan 2019). It was one of the first species both predicted and detected in transmission because it produces strong, narrow optical features (Seager &

Sasselov 2000; Charbonneau et al. 2002). $H\alpha$, by contrast, is sensitive to excited hydrogen in the $n = 2$ state, and therefore tends to trace hotter, more rarefied upper atmospheres whose observability can depend strongly on stellar UV flux and activity (Jensen et al. 2012). Na and $H\alpha$ need not behave in parallel, and a system that shows Na but not $H\alpha$ is not necessarily anomalous.

5.2 TOI-1288b: Implications of the Na I and $H\alpha$ Non-Detections

TOI-1288b exhibits no statistically significant absorption in either Na I or $H\alpha$ (Figures 4.2 and 4.1). One possibility is that TOI-1288b’s observable limb is muted at optical wavelengths by aerosols and/or a reduced scale height. High-altitude clouds or hazes can suppress atomic signatures by raising the effective continuum altitude and concealing deeper layers where stronger line absorption would otherwise contribute (Fortney 2005; Kreidberg et al. 2014; Madhusudhan 2019). This is a common theme in transmission spectroscopy, and it is one reason that Na line wings are less frequently recovered than Na cores in many hot-giant atmospheres. Even at high spectral resolution, where narrow line cores can theoretically be isolated, sufficiently opaque aerosols or a high mean molecular weight can reduce the effective scale height and diminish the measurable line contrast with noise (Madhusudhan 2019; Di Maio et al. 2023; Langeveld et al. 2022).

A second possibility is that the relevant absorbing populations are present, but not in the excitation state required for detection, especially in $H\alpha$. Jensen et al. (2012) showed that detectable $H\alpha$ absorption in a hot Jupiter is tied to excited hydrogen populations and emphasized that stellar variability must be treated carefully, because the host star can imprint transit-dependent $H\alpha$ structure. From

that perspective, the $H\alpha$ non-detection in TOI-1288b does not imply the absence of atmospheric escape or even the absence of extended hydrogen. It instead suggests that any excited-state hydrogen layer was below the sensitivity reached here during the observed epochs, or that the excitation conditions, especially the UV environment and activity state of the host star, were not favorable for producing an observable signal.

TOI-1288b is especially compelling in this context because it lies in the Neptunian desert. Planets in or near this region are often interpreted through an atmospheric-survival framework, where close-in intermediate-mass planets are expected to be especially vulnerable to irradiation-driven mass loss and envelope evolution. A resolved Na detection in a desert planet is not guaranteed even when sodium is present, because systematic error contributions such as deep stellar Na, low-SNR spectra, and overlapping stellar/planetary line structure can dominate the measurement. This is emphasized explicitly in Neptune-desert sodium work such as Seidel et al. (2022). The TOI-1288b non-detections therefore provide the conservative observational constraint that if Na I or $H\alpha$ absorption is present, it lies below the sensitivity achieved here.

5.3 TOI-640b: Sodium Detection and Hydrogen Non-Detection in Context

TOI-640b exhibits a significant Na I detection (Section 4.3.2) but no statistically significant $H\alpha$ absorption (Section 4.3.1). This combination is physically plausible. Sodium has been detected repeatedly in hot-planet atmospheres since the early space-based and ground-based measurements (Charbonneau et al. 2002; Snellen et al. 2008; Redfield et al. 2008), and line-resolved high-resolution detec-

tions commonly report Na D line contrasts at the several-tenths-of-a-percent level depending on target and metric (Wyttenbach et al. 2015; Zák et al. 2019). In contrast, H α transmission signals are not ubiquitous and are generally interpreted as diagnostics of excited hydrogen populations in hot upper atmospheres that may be sensitive to stellar variability (Jensen et al. 2012).

In the present work, the weighted-mean core depths measured for TOI-640b are approximately $0.393 \pm 0.090\%$ for D₂ and $0.204 \pm 0.085\%$ for D₁, with the combined integrated significance reaching 4.8σ . These amplitudes are smaller than the canonical HD 189733b contrasts reported by Wyttenbach et al. (2015), who measured $0.64 \pm 0.07\%$ for D₂ and $0.40 \pm 0.07\%$ for D₁, but they are clearly of the same order. They are also comparable, though somewhat weaker, than the Na depths reported by Zák et al. (2019) in WASP-76b and WASP-127b, where measured line depths are typically in the ~ 0.6 – 1% range and detections span roughly 4 – 9σ depending on the target and metric. This comparison matters because it places the TOI-640b sodium signal in the regime of plausible hot-giant Na absorption rather than at an anomalous amplitude that would immediately suggest an artifact. That broader landscape is summarized quantitatively in Figure 5.1 and in compact form in Table 5.1.

That in turn supports an interpretation in which TOI-640b’s atmospheric limb contains a sufficiently extended region of neutral sodium that the line cores remain measurable and are not fully masked by aerosols at the altitudes probed here. The H α non-detection does not argue against that interpretation. H α detections are not ubiquitous even among strongly irradiated giants, and when present they are generally interpreted as signatures of hotter, more excited upper atmospheres. It is therefore entirely consistent to detect Na, which traces neutral species at lower to intermediate altitudes, without also detecting H α , which requires a significant

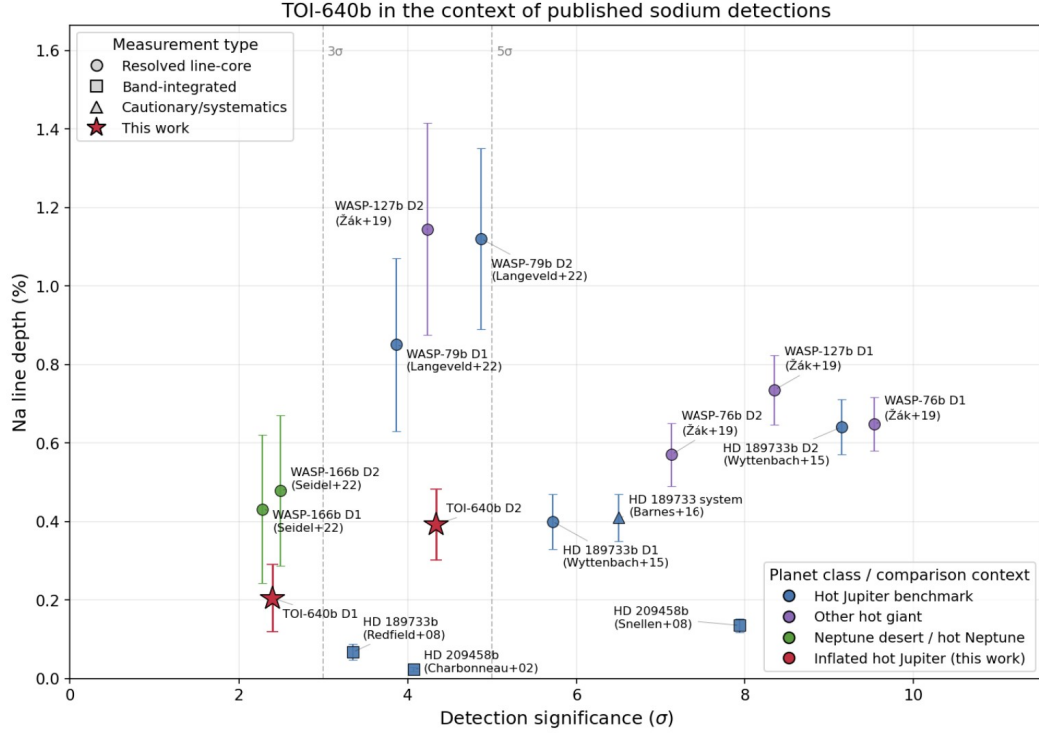


Figure 5.1: Comparison of NaI D₂ and D₁ line depths and detection strengths for TOI-640b (this work) against a benchmark set from the literature (Wytttenbach et al. 2015; Zák et al. 2019; Charbonneau et al. 2002; Snellen et al. 2008; Barnes et al. 2016; Seidel et al. 2022; Langeveld et al. 2022). Colors indicate the planet class or comparison context, while marker shape indicates the measurement type: circles denote resolved line-core measurements, squares denote band-integrated measurements, and triangles denote a cautionary/systematics-dominated case. Because the figure combines dedicated analyses with homogeneous survey measurements, and because passband definition, line-depth metric, and analysis method differ among studies, it should be interpreted as an order-of-magnitude contextualization rather than a fully homogeneous comparison.

Table 5.1: Compact comparison of TOI-640b with a small set of resolved Na I benchmark detections. To keep the comparison as homogeneous as possible, only the D₂ line is tabulated here. This choice follows the practice of Langeveld et al. (2022), who note that D₂ is clearly resolved across their survey while D₁ is less significant in some systems. Early bandpass detections and cautionary/systematics-dominated cases are discussed in the text and shown in Figure 5.1, but are not included in this compact table. Benchmark values are drawn from Wyttenbach et al. (2015), Zák et al. (2019), Seidel et al. (2022), and Langeveld et al. (2022).

System	D ₂ depth (%)	D ₂ significance	Context
TOI-640b	0.393 ± 0.090	4.3σ	this work
HD 189733b	0.64 ± 0.07	9.1σ	benchmark hot Jupiter
WASP-76b	0.57 ± 0.08	$\sim 7.1\sigma$	ultra-hot Jupiter
WASP-127b	1.144 ± 0.270	$\sim 4.2\sigma$	low-density giant
WASP-166b	0.479 ± 0.192	2.5σ	Neptune-desert comparison
WASP-79b	1.12 ± 0.23	$\sim 4.9\sigma$	homogeneous-survey benchmark

excited hydrogen population along the line of sight.

5.4 Assessing Robustness: the Ca I Control Residual and Stellar-Line Contamination

The dominant interpretive caveat for the TOI-640b Na detection is the behavior of the Ca I 6162.17 Å control line (Figure 4.5). While the Ca test yields no convincing planetary Ca detection, localized residual structure near the Ca line core demonstrates that the reduction can leave structured residuals in deep stellar lines. This matters because strong-line transmission spectroscopy is susceptible to transit-coupled stellar line-profile effects, including center-to-limb variation (CLV) and Rossiter–McLaughlin (RM) distortions, which can imprint signals at or near the cores of strong lines (Yan et al. 2017; Barnes et al. 2016). The geometry dependence of that problem is illustrated in Figure 5.2, which shows directly how CLV-related signals vary with transit configuration and therefore why line-

centered residuals near deep stellar features must be treated cautiously.

A useful historical comparison is Redfield et al. (2008), which reports a ground-based Na detection and conducts an explicit Ca I control-line check (Ca I 6122 Å), finding no corresponding control-line absorption. The clean control-line behavior in that case was used to argue against generic systematics producing a spurious sodium signal (Redfield et al. 2008). Figure 5.3 makes that parallel clear. In the present work, the Ca residual does not invalidate the Na detection, but it motivates a more conservative perspective. The sodium feature is best interpreted as a strong candidate detection that should be re-tested under explicit RM/CLV treatments and reference-frame diagnostics (stellar versus planetary rest frame), consistent with modern cautions in high-resolution work (Yan et al. 2017; Seidel et al. 2022).

The work of Zák et al. (2019) provides a useful methodological comparison here as well. Their analysis explicitly monitors stellar activity with Ca I and Mg I control lines and interprets non-significant control behavior as evidence that the sodium detection is unlikely to be driven by stellar variability. Figure 5.4 is useful in here, because it shows the kind of quiet control-line behavior that strengthens a sodium claim in the literature. In the present case, the calcium control is not entirely featureless, and the conservative interpretation is therefore that related transit-coupled line-profile effects (RM/CLV behavior, normalization residuals, or small alignment errors) could plausibly contribute to some fraction of the apparent sodium absorption. The most important next step is therefore to test whether the sodium signal is more coherent in the planetary rest frame than in the stellar rest frame and whether it survives explicit RM/CLV modeling, as is increasingly standard.

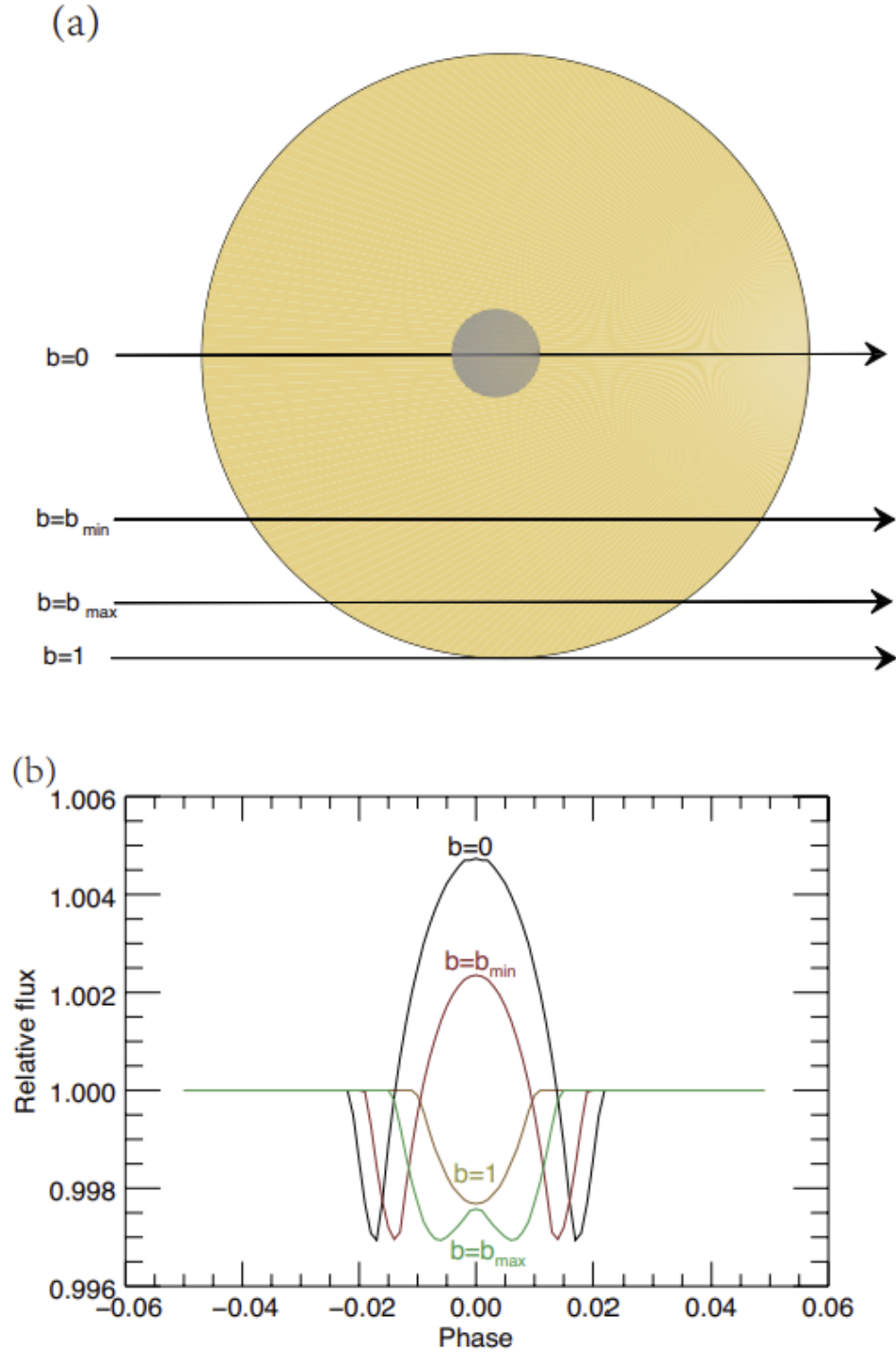


Figure 5.2: Illustration of center-to-limb variation (CLV) effects in Na I transmission spectroscopy from Yan et al. (2017, their Fig. 10). This figure demonstrates how CLV imprints transit-dependent signals whose amplitude and morphology depend on transit geometry (impact parameter), motivating caution when interpreting line-core residuals in strong stellar lines.

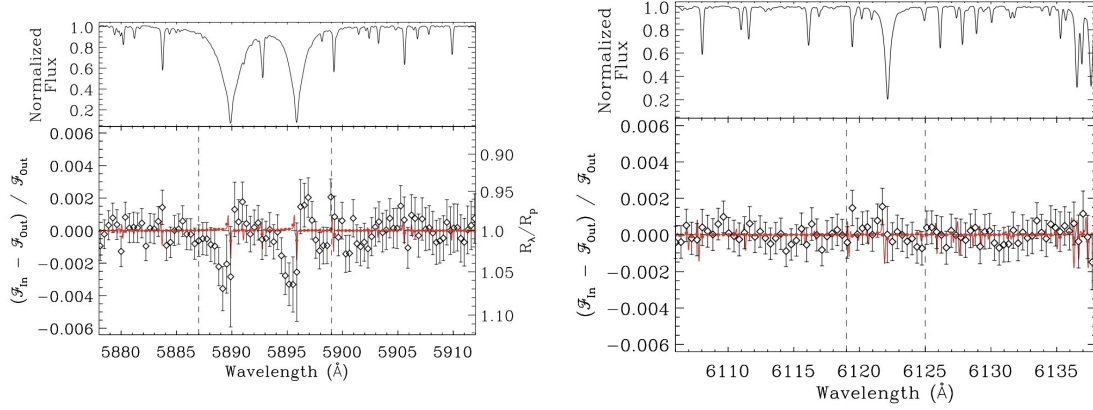


Figure 5.3: Benchmark high-resolution ground-based Na transmission detection and control-line test from Redfield et al. (2008, their Figs. 1–2). *Left:* Na I detection in HD 189733b. *Right:* Ca I control-line analysis (Ca I 6122 Å) showing no corresponding absorption, used to argue against generic systematics.

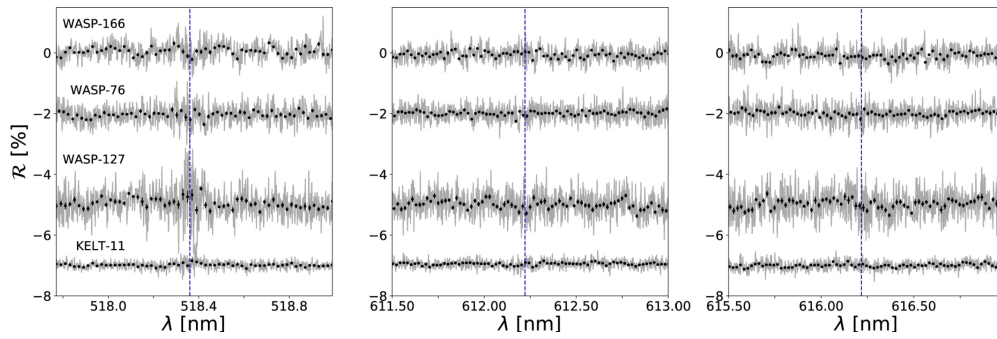


Figure 5.4: Example of Ca I and Mg I control-line behavior used to monitor stellar activity in a high-resolution Na detection study, from Zák et al. (2019, their Fig. 3). In that work, non-significant control-line behavior is used to argue that the Na detection is unlikely to be driven by stellar variability.

5.5 Comparison to Literature Sodium Detections

Direct quantitative comparisons between Na detections require care because the measured depth depends on the passband definition, binning, and whether a Gaussian line contrast or a band-integrated metric is reported (Langeveld et al. 2022). Nevertheless, a meaningful comparison can still be made at the level of approximate line-core contrast and detection significance when the observational framework is similar.

Wytenbach et al. (2015) provide a benchmark resolved sodium detection with HARPS for HD 189733b, measuring core contrasts of $0.64 \pm 0.07\%$ in D₂ and $0.40 \pm 0.07\%$ in D₁ with high significance. Zák et al. (2019) detect sodium in WASP-76b at approximately $7\text{--}9\sigma$ and in WASP-127b at approximately $4\text{--}8\sigma$, with line depths typically in the $\sim 0.6\text{--}1\%$ range depending on the line and fitting metric. Langeveld et al. (2022) expand this picture with a homogeneous survey of ten hot and warm giants, providing one of the clearest comparative views of sodium line depths and morphologies across a broader sample. Figure 5.5 is especially useful in this context because it shows that the detailed morphology and relative prominence of the D₂ and D₁ components vary substantially from system to system.

Against that backdrop, the TOI-640b sodium detection, 4.8σ combined, with D₂ stronger than D₁, sits comfortably within the range that the field would recognize as a credible line-resolved sodium signal. At the same time, the calcium residual remains the central reason to treat it more cautiously than a clean, uncontested benchmark case. In that case, Figure 5.1 and Table 5.1 are best read together. Figure 5.1 shows that TOI-640b lies in a plausible part of parameter space relative to other detections, while Table 5.1 makes clear that its D₂ depth

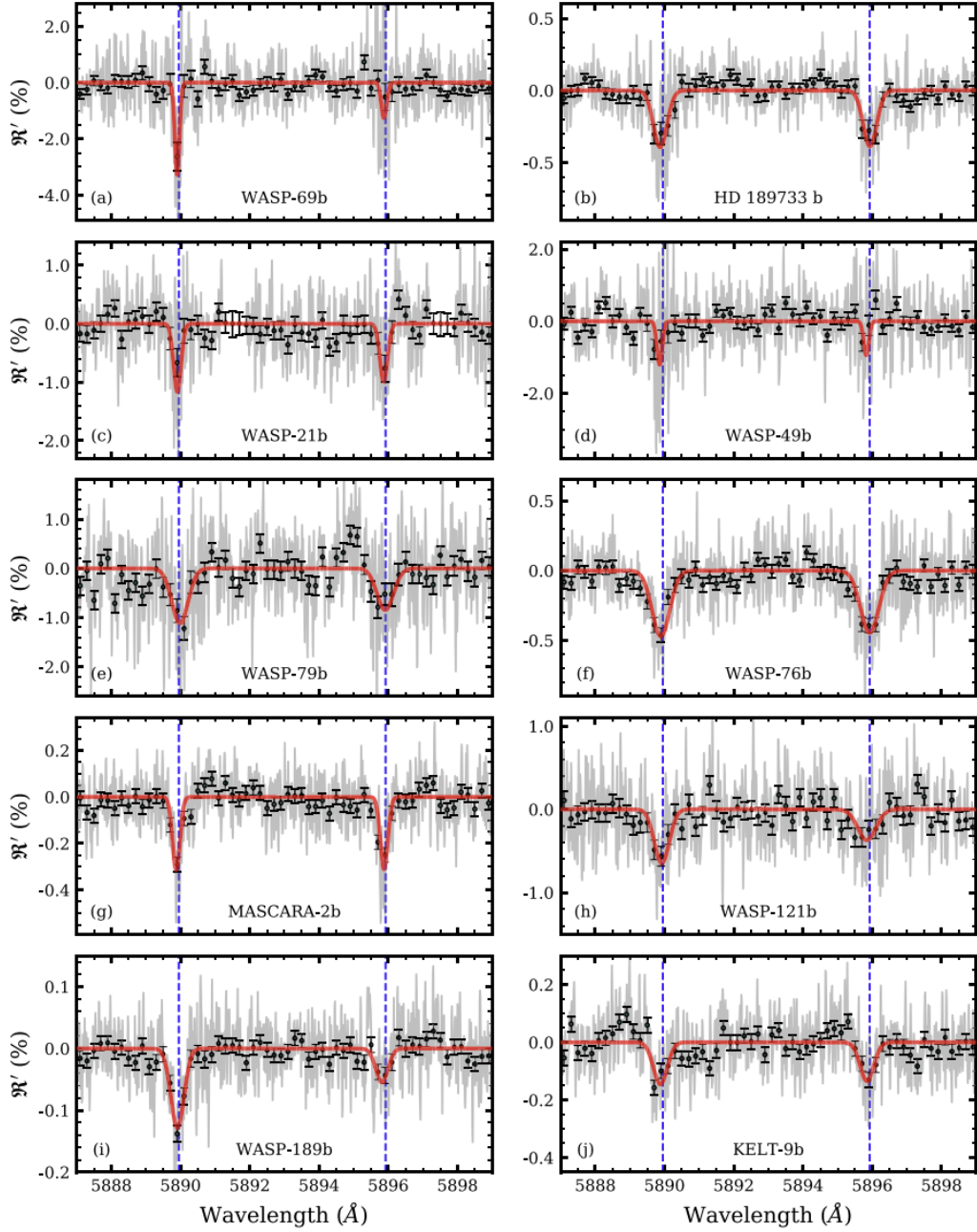


Figure 5.5: High-resolution NaI transmission spectra for ten hot/warm giant planets from Langeveld et al. (2022, their Fig. 5), shown to contextualize the range of Na line depths and morphologies obtained with a homogeneous analysis.

and significance are moderate rather than extreme within the current literature sample.

5.6 Speculative Implications

Up to this point, the discussion has stayed in a deliberately conservative register. Non-detections do not prove the absence of an atmosphere, detections must be stress-tested against stellar contamination, and the safest conclusions are the ones that survive control lines, alternative reductions, and repeat observations. For a moment, though, it is worth stepping outside that conservative regime and asking a perhaps more volatile but more interesting question: if these detections and non-detections are substantial, what kind of planets and systems might they be describing?

If the TOI-1288b non-detections are taken at face value, one interpretation is that this planet may already be deep into the aftermath phase of close-in atmospheric evolution. In that reading, TOI-1288b would not be a Neptunian-desert survivor whose observable atmosphere has already been sculpted into something compact, aerosol-rich, high-mean-molecular-weight, or otherwise spectroscopically muted. The early lives of close-in planets are especially important here. Stellar X-ray and EUV histories diverge strongly for the first few hundred Myr depending on stellar rotation, and that spread can drive very different atmospheric outcomes for planets that begin with similar bulk properties (Tu et al. 2015; Owen 2019). If TOI-1288b really is quiet in both Na I and H α , that may point to a world whose primordial low-density envelope has already been heavily processed; not necessarily erased, but compressed into a remnant atmosphere that no longer presents the large, clean optical scale height of an easy transmission target. In that picture,

TOI-1288b is a fossil of atmospheric loss.

A more specific version of that same theory is that TOI-1288b could be telling us as much about its star as about itself. TOI-1288 is a late G dwarf, and its present-day properties are at least consistent with a relatively quiet host. Knudstrup et al. (2023) report a low projected rotation velocity and find the star to be inactive based on HARPS-N activity indicators, including $H\alpha$ and the S-index, the latter serving as a proxy for chromospheric Ca II H and K emission. A present-day lack of $H\alpha$ may therefore indicate that the host star is not currently pumping the upper atmosphere hard enough in the UV to populate a detectable excited-hydrogen layer, even if escape was much more intense earlier in the system’s history (Jensen et al. 2012; Tu et al. 2015). Conversely, if the host star was highly active early on, the present null result could be what one would expect from a planet that has already endured the most violent phase of irradiation-driven sculpting. TOI-1288b may be a planet whose atmosphere tells us that it is on the quieter, more evolved side of its history.

TOI-640b invites almost the opposite interpretation. If the sodium detection and $H\alpha$ non-detections are taken as accurate measurements, the clearest picture is a strongly stratified atmosphere, with a lower-to-middle atmosphere with an extended, relatively accessible reservoir of neutral sodium, overlain by an upper atmosphere that is not presently driven into the excited-hydrogen regime. In that interpretation, TOI-640b is not necessarily a planet in the act of dramatic blow-off so much as a planet whose atmosphere is transparent enough for alkali absorption to appear, but whose thermosphere is either cooler, less UV-pumped, or less extended than other $H\alpha$ -bright systems (Madhusudhan 2019; Jensen et al. 2012). That would make the planet’s transmission spectrum physically layered. Such a result would hint at a host-star environment that is strongly irradiating

in the broad sense needed to keep the atmosphere inflated, but not so extreme in high-energy output that the upper atmosphere dominates the optical data.

Taken one step further, TOI-640b data may describe a system whose atmosphere survived a complicated dynamical history. The nearly polar orbit and outer companion already suggest that the system did not arrive at its present architecture by the calmest possible route (Knudstrup et al. 2023). If the Na I detection is real, one can imagine that the giant envelope either survived those extreme dynamics because it was always massive and resilient, or that the migration history placed the planet into its present configuration before the atmosphere had largely assembled and stabilized. The absent $H\alpha$ would then sharpen that story further, suggesting that the planet is in a comparatively stable post-migration state.

TOI-1288b could represent the lower-mass branch of close-in evolution, where irradiation and time conspire to strip, compact, or chemically mute the observable atmosphere. TOI-640b could represent the higher-mass branch where the envelope is robust enough to remain puffy and cause a relatively strong spectroscopic signal even after intense irradiation and possible dynamical excitation. These measurements could represent two snapshots of what mass, irradiation, and time can do to the observability of close-in atmospheres.

This is also the point at which this project starts to lean toward more contentious worlds, including K2-18b. On the surface, K2-18b seems far removed from sodium in hot Jupiters and $H\alpha$ in a desert planet. But the conceptual bridge is shorter than it looks. *JWST* observations of K2-18b have already pushed the field from finding evidence of an atmosphere to asking what kind of world it is as a whole. The 2023 *JWST* transmission spectrum revealed CH_4 and CO_2 in a hydrogen-rich atmosphere, a result that was interpreted as consistent with a possible Hycean scenario (Madhusudhan et al. 2025). However, the very next wave of

interpretation showed how unstable such conclusions can be, when Wogan et al. (2024) argued that the same data can be explained by a gas-rich mini-Neptune with no habitable surface at all. The 2025 Mid-Infrared Instrument (MIRI) follow-up pushed the discussion even further, raising the possibility of DMS/DMDS (dimethyl sulfide and dimethyl disulfide) in the atmosphere (Madhusudhan et al. 2025), while later analyses argued that the current data do not yet satisfy a robust standard of evidence for an unambiguous biosignature detection (Stevenson et al. 2025; Tennyson & Yurchenko 2025).

That debate is the future version of the same problems faced by this thesis. Before a field can claim biosignatures, it must learn how to analyze a line. Before it can infer oceans, it must know how to separate real chemistry from contamination and physical structure from retrieval degeneracy. Atomic transmission spectroscopy is part of the training ground for the methods we use to answer the question of life on other worlds. The discipline demanded by Na I, H α , and control-line analysis (care with reference frames, care with stellar contamination, care with forward models, care with non-detections) is the same discipline that will decide whether future claims about habitable sub-Neptunes or biosignature candidates survive first contact with skepticism (Meadows et al. 2018; National Academies of Sciences, Engineering, and Medicine 2018; Tennyson & Yurchenko 2025).

Through these ideas, the arc of this thesis becomes slightly larger than salt and hydrogen in two exoplanets. TOI-1288b may be showing us what an atmosphere looks like when irradiation has already done most of its long work. TOI-640b may be showing us what it looks like when a giant planet remains inflated, dynamically scarred, but still spectroscopically legible. The planets in this thesis are probably not habitable worlds, and sodium is not a biosignature, but the techniques of

analysis required to interpret them correctly are the same ones the field will need when the molecules become more provocative, and the stakes become much larger.

Chapter 6

Conclusions and Future Work

This thesis began from a simple observational question with wider implications: under what conditions are common optical tracers such as Na I and H α measurable in exoplanet transmission spectra, and what do detections or non-detections imply about atmospheric structure, excitation, and evolution? Behind that question lay several larger ones that have run through the entire thesis from the beginning, namely, how do we move from the growing census of exoplanets to a physically grounded understanding of what their atmospheres are made of, how they behave under irradiation, and how confidently we can separate planetary signals from the light of the stars they orbit?

The introduction framed this work in the broader development of astronomy and exoplanet science, from the expanding observational reach of the field to the present era of population-level exoplanet demographics and atmospheric characterization. I argued that atmospheric spectroscopy matters because it can identify specific species and connects detection statistics to physical interpretation. A measured absorption line is evidence about atmospheric extent, temperature, excitation, chemistry, and, in some regimes, escape. I also emphasized two especially useful population contexts for this thesis. I spoke about the Neptunian desert, where irradiation and atmospheric loss are thought to reshape planetary demographics, and the broader class of hot, low-density giant planets whose large scale

heights make them favorable targets for transmission spectroscopy. TOI-1288b and TOI-640b were selected because they occupy different and complementary parts of the problem space.

Chapter 2 then placed both systems in their observational context. TOI-1288b is a short-period super-Neptune in the Neptunian desert, a regime where atmospheric survival and atmospheric observability do not necessarily go hand in hand. TOI-640b, by contrast, is an inflated hot Jupiter with a nearly polar orbit, combining a geometry that is dynamically interesting with an atmosphere that ought to be comparatively favorable for transmission spectroscopy. Both systems were discovered by *TESS* and then characterized through high-resolution spectroscopic follow-up. Both planets sit at the intersection of modern exoplanet discovery and modern exoplanet characterization. They are products of the current survey era, and they serve as case studies for what can actually be extracted from current high-resolution datasets.

Chapter 3 developed the analysis framework used to address the central measurement problem of the thesis. The goal was to construct transmission spectra by organizing exposures into in- and out-of-transit subsets, extracting and normalizing the relevant spectral regions, combining the individual spectra through inverse-variance weighting, and then comparing the resulting master in-transit and out-of-transit spectra. In practice, the project was as much about building a defensible pipeline as it was about generating line depths from a final plot. That meant making choices about wavelength windows, normalization strategy, temporal organization, error propagation, telluric awareness, and rest-frame handling. The development of the TOI-1288b pipeline was especially useful in this respect, because reproducing a non-detection forced the analysis to confront subtle issues of normalization and coaddition before more suggestive signals were encountered

elsewhere. The TOI-640b analysis extended that framework further by including wavelength-alignment corrections and explicit planet-rest-frame shifting before coaddition, so that any real planetary sodium signal would add coherently.

The final empirical outcomes of the thesis were presented in Chapter 4. TOI-1288b shows no statistically significant absorption in either $H\alpha$ or the Na I D doublet. TOI-640b likewise shows no statistically significant $H\alpha$ absorption, but it does exhibit a significant Na I signal. For TOI-640b, the weighted-mean line-core depths are approximately $0.393 \pm 0.090\%$ for D_2 and $0.204 \pm 0.085\%$ for D_1 , corresponding to mean-depth significances of 4.3σ and 2.4σ , respectively. When treated with the integrated, equivalent-width-like metric adopted in the results chapter, the sodium doublet reaches a combined detection significance of approximately 4.8σ . The calcium control analysis, though, revealed localized residual structure near the stellar Ca line, immediately raising the question of how confidently the sodium result can be interpreted as planetary rather than stellar or reduction-related.

The non-detections in TOI-1288b are informative because they are non-detections in two different tracers that probe different physical regimes. Na I and $H\alpha$ need not behave in parallel. Sodium is typically interpreted as a tracer of neutral alkali absorption in the lower-to-middle atmosphere, while $H\alpha$ is sensitive to excited-state hydrogen and therefore to hotter, more rarefied upper layers whose observability may depend strongly on stellar UV excitation and activity (Madhusudhan 2019; Jensen et al. 2012). A non-detection in both tracers does not immediately imply that TOI-1288b lacks an atmosphere, instead constraining the combination of scale height, vertical abundance structure, aerosols, excitation state, and observational sensitivity that determines whether a line is measurable in transmission at all. The most conservative reading is that any Na I or $H\alpha$ absorption present

in TOI-1288b lies below the sensitivity achieved here.

That result matters in part because TOI-1288b resides in the Neptunian desert. One of the broader lessons of the thesis is that observability is not equivalent to atmospheric existence. A planet can retain an atmosphere and still fail to produce a detectable sodium or hydrogen line in a given dataset. High-altitude aerosols, reduced scale height, high mean molecular weight, or simply insufficient excitation of the relevant upper-atmosphere populations can all suppress the signals sought here (Madhusudhan 2019; Owen 2019; Seidel et al. 2022). The TOI-1288b non-detections therefore support the broader picture in which the Neptunian desert is shaped by irradiation-driven mass loss and atmospheric evolution, and they reinforce the idea that the desert is a regime in which the atmospheres that remain may be difficult to access observationally in simple optical tracers.

TOI-640b provides a contrasting case. Here the sodium detection and hydrogen non-detection together present a physically coherent picture. It is entirely plausible that TOI-640b possesses an extended neutral sodium-bearing atmosphere at pressures and altitudes accessible to line-core transmission spectroscopy, while lacking an $H\alpha$ signal strong enough to indicate a comparably detectable population of excited hydrogen in the upper atmosphere. In the broader literature, line-resolved sodium detections commonly fall in the several-tenths-of-a-percent regime, and in that sense TOI-640b does not stand apart as implausibly strong/weak or oddly shaped. Its measured line depths place it within the range of established hot-giant sodium detections, even if it is not among the strongest of them (Wytenbach et al. 2015; Zák et al. 2019; Langeveld et al. 2022).

This thesis does not support the claim of a completely settled sodium detection. The Ca I control-line residual is the main reason for caution. The purpose of the calcium test was to assess whether the transmission-spectroscopy pipeline can

generate line-centered residuals in a strong stellar feature even when no planetary signal is expected. The answer appears to be yes, sort of. The calcium spectrum does not show a convincing planet-rest-frame line-centered atmospheric signal, but it does show enough structure near the stellar line to indicate that stellar contamination and/or reduction residuals remain plausible contributors. That concern is supported by the known vulnerability of strong-line transmission spectroscopy to center-to-limb variation and Rossiter–McLaughlin distortions, both of which can imprint transit-coupled structures in stellar line cores (Yan et al. 2017; Barnes et al. 2016). This is especially relevant for TOI-640b because its nearly polar geometry makes it a particularly interesting, and potentially particularly delicate, case for line-profile analysis.

Chapter 5 therefore arrived at a deliberately measured interpretation. The sodium signal in TOI-640b is best regarded as a strong candidate detection whose amplitude and significance are consistent with credible planetary absorption, but whose ultimate robustness depends on whether it survives more explicit treatment of stellar-frame effects. This is not a weakness of the project so much as an honest reflection of what high-resolution transmission spectroscopy demands. The field has reached the point where a statistically significant line feature is not, by itself, always the end of the story. Strong claims increasingly require tests of rest-frame coherence, control-line behavior, and explicit modeling of stellar contamination. In that respect, one of the most useful outcomes of this thesis is methodological, as it demonstrates that the combination of a positive sodium result and a non-trivial control-line residual is still scientifically productive because it points directly toward the next analyses that matter most.

Together, the contrasting results for TOI-1288b and TOI-640b reinforce a broader lesson about atmospheric characterization. Whether a signal is observable

depends not only on whether an atmosphere exists, but on which atmospheric layers are sampled, how the absorbing species are distributed vertically, how clouds and hazes shape the limb, and how effectively stellar contamination can be recognized and controlled. In TOI-1288b, the outcome is a pair of non-detections that remain compatible with several physically reasonable atmospheric scenarios, including muted or difficult-to-access optical tracers in a desert planet. In TOI-640b, the outcome is more encouraging but also more cautionary. Sodium appears measurable in an inflated, strongly irradiated giant planet, but the calcium control makes clear that strong-line detections in unusual systems should be interpreted conservatively until stellar-line effects are explicitly modeled out.

Therefore, the thesis answers its original question in a way that is necessarily mixed. Yes, optical tracers are measurable in these kinds of systems, but not uniformly, and not without careful attention to the distinction between statistical significance and physical certainty. Yes, non-detections are informative, but only when interpreted as limits on observability rather than as blanket statements about atmospheric absence. And yes, a sodium detection at the several-sigma level is exciting, but it becomes most meaningful when placed in the context of controls, comparison samples, and the increasingly sophisticated standards of the field.

6.1 Future Work

The clearest next step for this project is to deepen the interpretation of the TOI-640b sodium result through more explicit modeling. The preliminary forward-model comparison presented in Chapter 4 shows that the line can be placed into a physical atmospheric framework, but that comparison should be ex-

tended substantially. A more developed forward-modeling program would explore the dependence of the Na line profile on temperature structure, sodium abundance, scale height, cloud opacity, and mean molecular weight, ideally in a way that connects the measured line depths and widths to a family of physically plausible atmospheric states. Tools such as `petitRADTRANS` are especially well suited to this task, because they provide a practical route from assumed atmospheric structure to synthetic transmission spectra that can be compared directly with the measured data. The goal of that exercise would be to identify which classes of atmospheres are consistent with the measured sodium line and which are not.

A second priority is explicit Rossiter–McLaughlin and Center–To–Limb Variation analysis. This is the most important methodological future-work direction emerging from the thesis. The present pipeline demonstrates that a sodium signal is present in the final TOI-640b transmission spectrum, but it does not yet prove that the signal is fully separable from transit-coupled stellar line-profile effects. Future work should therefore construct a model of the stellar Na and Ca line behavior during transit under the measured system geometry, including the effects of stellar rotation, center-to-limb spectral variation, and the Rossiter–McLaughlin distortion (Yan et al. 2017; Barnes et al. 2016). The nearly polar orbit of TOI-640b makes this especially worthwhile, because the transit trajectory samples the stellar disk in a way that is dynamically unusual and therefore potentially rich in differential line-profile behavior. The central question is whether the sodium feature remains coherent and significant once an explicit stellar contamination model is removed. If it does, confidence in the planetary interpretation increases substantially. If it weakens, that outcome is still valuable, because it clarifies how much of the present signal was likely stellar in origin.

Related to this is the need for stronger reference-frame diagnostics. One of the

simplest and most decisive tests available in high-resolution transmission spectroscopy is to ask whether the signal is more stable and more sharply localized in the planetary rest frame or the stellar rest frame. A genuinely planetary signal should become more coherent when shifted into the planet frame before coaddition. A stellar-origin residual, by contrast, may remain sharper in the stellar frame. Applying this test systematically to both the sodium feature and the calcium control would provide a more direct measure of whether the absorption structure behaves like a planetary atmospheric signal or like a transit-modulated stellar artifact. This should be paired with injection–recovery tests, in which synthetic absorption signals of known depth and width are inserted into the data to assess how reliably the present pipeline can recover them under the actual noise properties of the observations.

Additional observations are also an obvious and worthwhile path forward. For TOI-640b, repeat transit spectroscopy would test the reproducibility of the sodium detection and the stability of the calcium residual. Repetition matters because one of the most effective ways to distinguish atmospheric signals from stochastic stellar or reduction-related effects is to ask whether the same line shape and significance recur across independent transits. A second or third sodium detection with similar amplitude, especially after improved RM/CLV treatment, would substantially strengthen the claim. For TOI-1288b, more data could be just as important. Its current non-detections are informative, but a larger in-transit dataset would allow lower upper limits and a better test of whether TOI-1288b is truly quiet in NaI and H α or simply below the present sensitivity threshold. Because TOI-1288b lies in the Neptunian desert, even improved non-detections would remain scientifically useful.

Future work should also expand the range of species examined. In the present

thesis, sodium and $H\alpha$ were chosen for good reasons. They are accessible, physically interpretable, and representative of two different atmospheric regimes. However, a broader atomic inventory would help disentangle the interpretation. Potassium would be a natural next optical alkali tracer. Additional control lines, such as Mg I or other nearby stellar features, would provide stronger tests of activity- or normalization-driven residual structure. At longer wavelengths, helium at 10833 Å would be an especially attractive target in future observations, since it has emerged as a powerful tracer of upper-atmosphere escape in strongly irradiated planets. The more multi-species this analysis becomes, the easier it will be to distinguish between a genuinely extended atmosphere, a cloud-muted lower atmosphere, and an upper atmosphere whose excitation conditions vary from species to species.

A further direction is to connect the high-resolution measurements made here with broader atmospheric constraints from low-resolution or space-based spectroscopy. One of the major lessons of recent exoplanet atmospheric work is that different resolutions answer different questions. High-resolution spectra are excellent for narrow line cores and dynamical separation of signals, while broader wavelength coverage is often needed to constrain abundances, cloud properties, and thermal structure more globally. The strongest long-term interpretation of TOI-640b and TOI-1288b would therefore come from combining the kind of line-resolved optical work presented here with broader forward-model and retrieval frameworks that can use multi-wavelength constraints together; that is how a measured sodium line becomes part of a full atmospheric picture rather than an isolated detection.

Finally, there is future work in the most literal interpretation, as this thesis should function as a foundation. One of its practical outcomes is a transmission-spectroscopy pipeline that has now been tested on a non-detection case, a likely

detection case, and a control-line case. That is a useful starting point for additional systems and additional species. The pipeline can be generalized, strengthened, and made more automatic; the forward-model comparison can become a more systematic physical inference engine; the treatment of tellurics and wavelength alignment can be refined further; and the transition from line detection to atmospheric interpretation can be made more rigorous. These elements are a very substantial part of the science, because this field advances by learning how much of a spectral feature belongs to a planet, how much belongs to a star, and how confidently we can tell the difference.

In the end, that is where this project leaves off. TOI-1288b and TOI-640b did not produce a pair of simple, symmetrical answers, instead giving us something even more useful. We now have a non-detection in a scientifically important Neptunian desert planet, a promising sodium detection in an inflated hot Jupiter, a cautionary control-line result that sharpens the interpretation of that detection, and a set of next steps that are both technically achievable and well motivated. The project therefore closes with the feeling that the problem is unfinished, and yet also that it has come into much better focus. That is, in its own way, a satisfying ending for a thesis and a good beginning for whatever comes next.

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