

A population view of transiting hot giant exoplanets: Tracing Fe and Ti chemistry with ESPRESSO and MAROON-X

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ABSTRACT

Hot and ultra-hot Jupiters offer a unique laboratory for studying atmospheric chemistry at the population level using ground-based high-resolution spectroscopy. Iron (Fe) and titanium (Ti) are key tracers of thermal and chemical structures, yet they exhibit markedly different observational trends across the population. We present a homogeneous re-analysis of high-resolution transmission spectra for ten hot and ultra-hot Jupiters observed with ESPRESSO on ESO’s Very Large Telescope and MAROON-X on Gemini-North. We searched for neutral Fe and Ti absorption and performed injection–recovery tests using forward models spanning a range of Ti-depletion levels and temperature–pressure profiles. To enable direct comparison across planets observed with different instruments and signal-to-noise ratios, we introduced the relative cross-correlation metric, $\Delta_{\text{Ti-Fe}}$. We detect Fe in seven planets and Ti in four planets at significances above 5σ . Across the population, $\Delta_{\text{Ti-Fe}}$ decreases sharply towards lower equilibrium temperatures. Under the assumption of equal Ti depletion across planets, isothermal models fail to reproduce this trend, instead requiring a temperature-dependent depletion of Ti that increases towards cooler planets, consistent with cold-trapping processes in cooler atmospheres. Models with inverted temperature–pressure profiles naturally reproduce the decline without invoking such temperature-dependent depletion. In these atmospheres, Ti is converted into TiO in deeper, cooler layers and subsequently removed from the gas phase through condensation into Ti-bearing species, leading to a strong suppression of the observable atomic Ti signal while Fe remains largely atomic. Nevertheless, even in these gradient models, an additional overall depletion of Ti relative to Fe is required to match the hottest planets. Our results demonstrate that the observable refractory chemistry is governed by the interplay of molecular partitioning, ionisation, condensation, and cold-trapping processes, as well as the vertical structure of ultra-hot Jupiter atmospheres. Although these results reveal clear population-level trends, additional observations will be necessary to distinguish between temperature-dependent cold-trapping and overall depletion scenarios. Expanding homogeneous high-resolution surveys to larger and more diverse samples, targeting both emission and transmission observations, will refine these constraints and provide critical insights into the chemistry of strongly irradiated giant planets.

Key words. planets and satellites: atmospheres – planets and satellites: gaseous planets – techniques: spectroscopic – methods: observational

1. Introduction

Ultra-hot and hot Jupiters have long served as workhorses for atmospheric characterisation with ground-based high-resolution spectroscopy (e.g. Snellen et al. 2010; Brogi et al. 2012; Birkby et al. 2013; Hoeijmakers et al. 2018; Prinoth et al. 2022; Pelletier et al. 2023; Seidel et al. 2025), owing to their inflated radii and short orbital periods. Observed in both transmission and emission, their atmospheres probe extreme physical conditions and

provide unique insights into atmospheric chemistry and dynamics (e.g. Ehrenreich et al. 2020; Line et al. 2021; Pelletier et al. 2021; Brogi et al. 2023; Zhang et al. 2026).

Optical high-resolution spectrographs ($R \gtrsim 70,000$) have enabled the detection of numerous refractory metals in these atmospheres, most notably iron and titanium after their first discovery in ultra-hot Jupiter atmospheres (Hoeijmakers et al. 2018). These detections have primarily relied on the cross-correlation technique (e.g. Snellen et al. 2010), which exploits the combined signal of hundreds to thousands of absorption lines to enhance weak planetary signatures above stellar and telluric contamination (see Birkby 2018; Snellen 2025, for recent reviews). Ap-

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plied systematically across multiple planets, this method enables comparative studies that reveal how physical and chemical processes shape observable atmospheric composition.

Observational studies have shown that iron is nearly ubiquitous in ultra-hot Jupiter atmospheres ($T_{\text{eq}} \gtrsim 2,200$ K). Both neutral and ionised iron have been detected across a broad range of equilibrium temperatures in transmission and emission observations (e.g., Borsas et al. 2019; Casasayas-Barris et al. 2019; Ben-Yami et al. 2020; Gibson et al. 2020; Hoeijmakers et al. 2020a; Nugroho et al. 2020; Stangret et al. 2020; Yan et al. 2020; Cabot et al. 2021; Cont et al. 2021; Kesseli & Snellen 2021; Kasper et al. 2021; Bello-Arufe et al. 2022b,a; Gandhi et al. 2022; Herman et al. 2022; Kesseli et al. 2022; Pai Asnodkar et al. 2022; Pino et al. 2022; Yan et al. 2022; Borsato et al. 2024; Johnson et al. 2023; Lowson et al. 2023; Ramkumar et al. 2023; Lesjak et al. 2025; Petz et al. 2025; Costa Silva et al. 2024; Stangret et al. 2024; Young et al. 2024; Bazinet et al. 2025; Basinger et al. 2025; Householder et al. 2025; Ramkumar et al. 2025; Vaulato et al. 2025a,b; Sanchez et al. 2025; van Sluijs et al. 2025; Yang et al. 2025; Lenhart et al. 2026; Bonidie et al. 2026). Titanium, by contrast, has proven more difficult to detect. While strong neutral and ionised Ti signatures are observed in some of the most strongly irradiated planets (e.g. Hoeijmakers et al. 2018; Cont et al. 2022; Prinoth et al. 2022; Stangret et al. 2022; Borsato et al. 2023; Jiang et al. 2023; Scandariato et al. 2023; Guo et al. 2024; D’Arpa et al. 2024; Simonnin et al. 2025; Prinoth et al. 2025; Zhang et al. 2026), many cooler objects, despite having clear iron detections, exhibit weak or entirely absent Ti (e.g. Hoeijmakers et al. 2020b; Merritt et al. 2020; Gandhi et al. 2023; Maguire et al. 2023; Pelletier et al. 2023). Additionally, there appears to be a paucity of TiO detections, with one robust ground-based detection confirmed across multiple spectrographs in WASP-189 b (Prinoth et al. 2022, 2023) and several other tentative detections awaiting confirmation (e.g. Nugroho et al. 2017; Sedaghati et al. 2017). Meanwhile, lower resolving-power observations with space-based observatories such as HST and JWST can struggle to unambiguously resolve spectral bands of TiO (e.g. Evans et al. 2016; Pelletier et al. 2026).

Detailed studies performing atmospheric retrievals and injection-recovery analyses of individual systems consistently find titanium to be depleted relative to iron. For example, the atmosphere of WASP-121 b ($T_{\text{eq}} \approx 2,350$ K, Delrez et al. 2016) exhibits significantly weaker Ti absorption compared to Fe across multiple independent studies (e.g. Gibson et al. 2022; Maguire et al. 2023; Pelletier et al. 2024; Hoeijmakers et al. 2024a; Prinoth et al. 2025). At somewhat lower equilibrium temperatures, Ti appears to vanish entirely from the observable atmosphere in planets such as WASP-76 b ($T_{\text{eq}} \approx 2,200$ K, Ehrenreich et al. 2020), where the abundance of iron and other refractory metals are consistent with stellar while Ti is comparatively significantly depleted (Gandhi et al. 2023; Pelletier et al. 2023). Similarly, with higher equilibrium temperatures, HAT-P-70 b, TOI-1518 b, and WASP-189 b, also exhibit depleted Ti relative to Fe, however, less so compared to cooler systems (Simonnin et al. 2025; Gandhi et al. 2023).

Several mechanisms have been proposed to explain this observed trend of titanium signals that are weaker than model predictions. One possibility is that the elemental abundance of Ti relative to Fe differs from that of the host star, for example as a result of formation processes in the protoplanetary disc. However, this scenario is generally considered unlikely, as both elements are refractory and are expected to be incorporated into planets primarily in solid form during formation, thereby largely preserving their relative abundances (e.g. Lothringer et al. 2021).

Another possibility is that titanium is preferentially removed from the atomic phase through recombination into molecules such as TiO. In this case, Ti may remain in molecular form but becomes undetectable in cross-correlation analyses using atomic Ti. However, this explanation is also challenged by low-resolution observations, which indicate that TiO itself can be significantly depleted in some ultra-hot Jupiter atmospheres (e.g., Evans et al. 2018; Pelletier et al. 2026). This suggests that additional processes must be involved that deplete the overall abundance of titanium-bearing species.

A third possible explanation is a cold-trap mechanism that removes titanium from the gas phase of the observable atmosphere through condensation and rainout processes (e.g. Evans et al. 2018; Hoeijmakers et al. 2020b). Titanium readily forms TiO and TiO₂ molecules, which can subsequently condense into refractory compounds such as perovskite (CaTiO₃) and other titanium oxides (Lodders 2002; Kitzmann et al. 2024). These condensates form even at relatively high temperatures, where Ti-species are expected to condense at approximately 1,600 K, compared to about 1,400 K for iron (Lodders 2003). In the intensely irradiated atmospheres of ultra-hot Jupiters, TiO is largely thermally dissociated on the dayside, while on the cooler nightside or in deeper atmospheric layers it can recombine and subsequently condense (Spiegel et al. 2009; Parmentier et al. 2013). Three-dimensional circulation models predict that these condensates can rain down towards the deep atmospheric layers fast enough to prevent efficient vertical mixing and the replenishment of titanium in the observable upper atmosphere (Parmentier et al. 2016). In theory, such a process could deplete titanium more efficiently than iron. However, since the 200 K difference between the condensation curves of Ti and Fe is small compared to the $\sim 1,000$ K day-to-night contrast in these planets (e.g. Splinter et al. 2025), both species are expected to condense together and form mixed, dirty grains (Helling et al. 2019). While TiO₂ has a relatively low self-condensation energy barrier (Lee et al. 2015) that can enable efficient heterogeneous nucleation (Fegley & Lodders 1996), the efficiency of this mechanism in preferentially removing Ti compared to Fe thus still needs to be demonstrated.

Taken together, these studies suggest that titanium depletion is a common feature of ultra-hot Jupiter atmospheres, but its physical origin remains to be confirmed. Disentangling the relative roles of molecular partitioning, ionisation, condensation, and cold trapping, therefore, requires systematic observational constraints across a wide range of planetary conditions. In particular, identifying trends with parameters such as equilibrium temperature, surface gravity, composition, and stellar irradiation may help distinguish between competing mechanisms. While historically most high-resolution studies have focused on individual benchmark planets, the field is now increasingly shifting towards homogeneous population-level analyses designed to identify such trends (e.g. Langeveld et al. 2022; Stangret et al. 2022; Gandhi et al. 2023; Lothringer et al. 2025). Such studies are essential for separating genuine observational trends from observational biases introduced by different instruments, analysis techniques, and data quality.

In this work, we present a homogeneous population study of iron and titanium absorption in the transmission spectra of ten hot and ultra-hot Jupiters observed with the ESPRESSO spectrograph on ESO’s Very Large Telescope and the MAROON-X spectrograph on Gemini North. We reanalysed all datasets using a consistent methodology and quantified the relative trend of Fe and Ti by comparing the observed population trends to forward-model predictions.

2. Observations and sample selection

Our study focuses on hot and ultra-hot Jupiters with high-resolution optical spectra obtained using either MAROON-X at Gemini-North (Seifahrt et al. 2018) or ESPRESSO at ESO’s Very Large Telescope at Paranal Observatory (Pepe et al. 2021). These instruments were chosen for their combination of high spectral resolution ($R \gtrsim 85,000$), broad wavelength coverage (ESPRESSO: 378 – 789 nm, MAROON-X: 500 – 920 nm) in the optical where iron and titanium absorb strongly, and their installation on 8 m class telescopes. These instruments enable sufficiently high signal-to-noise ratio (S/N) with relatively short exposures, thus limiting smearing of the exoplanet signal due to its rapidly changing line-of-sight velocity and thereby enabling the detection of weak metal absorption even in atmospheres with depleted abundances (e.g. Prinoth et al. 2025).

From the population of known gas-giant exoplanets ($0.75 \leq R_p [R_{\text{Jup}}] \leq 2.5$), we identified all systems observed in transmission with MAROON-X or ESPRESSO. In total, 16 planets match these criteria. Several systems were excluded from the final sample: KELT-4 A b, MASCARA-4 b, and KELT-7 b due to strong stellar pulsations (Eastman et al. 2016; Stangret et al. 2022; Zhang et al. 2022), which significantly distort the cross-correlation signals; WASP-19 b due to low signal-to-noise observations dominated by instrumental systematics (Sedaghati et al. 2021); KELT-17 b due to the peculiar chemical composition of its host star, which has been shown to hinder iron detection (see e.g. Stangret et al. 2022, and study in prep.); and KELT-9 b due to its extreme equilibrium temperature, which places it in a substantially different physical and chemical regime characterised by strong ionisation (e.g. Hoeijmakers et al. 2018; Kitzmann et al. 2018). The resulting sample used for our analysis therefore comprises ten hot and ultra-hot Jupiters.

Figure 1 illustrates the location of our targets in the radius–temperature plane relative to the broader gas-giant population. A full observational log of the included and excluded systems is provided in Appendix; see Table D.1. The data were obtained either directly from principal investigators of the respective observing programmes or retrieved from the ESO/Gemini archives if previously used in a peer-reviewed publication.

The ESPRESSO observations were reduced with the dedicated pipeline (v3.2.0) within the *esoreflex* environment (v2.11.5) provided by ESO and the ESPRESSO consortium. For the cross-correlation analysis, we used the non-blaze-corrected, 2D order-by-order spectra from fibre A (S2D products). However, for the telluric correction, the flux-calibrated 1D spectra from fibre A (S1D products) provide a better continuum fit and were used instead and then interpolated on the S2D orders. The ESPRESSO pipeline applies barycentric Earth radial velocity (BERV) corrections directly to the S2D spectra.

The MAROON-X data were reduced using the standard pipeline described in Seifahrt et al. (2020), which produces order-by-order spectra analogous to ESPRESSO S2D products. Due to differences in readout times between the red and blue arms, exposures were synchronised at the start but recorded separately and were therefore treated as independent observations. Since the pipeline does not produce flux-calibrated 1D spectra, we stitched the reduced data to construct a 1D time series for telluric correction (Prinoth et al. 2023). Unlike ESPRESSO, BERV corrections were not applied during reduction and were instead applied during the cross-correlation analysis.

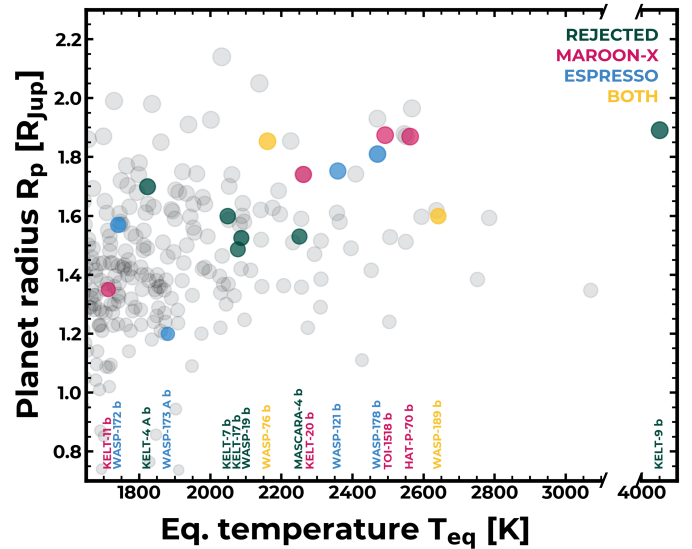


Fig. 1: Overview of the exoplanet population in the gas-giant regime with radii between 0.75 and 2.5 R_{Jup} , extracted from the NASA Exoplanet Archive on 12 June 2026. The parameter space shown corresponds to hot and ultra-hot Jupiters with equilibrium temperatures between 1500 and 4100 K. The planets included in our sample are colour-coded by the instrument with which they have been observed: MAROON-X in red, ESPRESSO in blue, and both in yellow. Rejected targets are displayed in green. We excluded MASCARA-4 b, KELT-4 A b, and KELT-7 b due to their orbits around pulsating stars; WASP-19 b due to low-S/N observations from its relatively faint host star; KELT-17 b due to its chemically peculiar Am host star; and KELT-9 b due to its high temperature, which probes a different chemical regime.

3. Methods

We carried out a homogeneous re-analysis of all datasets using the open-source package *tayph* (e.g. Hoeijmakers et al. 2018, 2020b; Prinoth et al. 2022; Borsato et al. 2023). It provides routines for telluric correction, masking, outlier rejection, and cross-correlation of the form

$$C(v, t) = \sum_{i=0}^N F_i(t) T_i(v), \quad (1)$$

where $T(v)$ represents the cross-correlation template shifted to a radial velocity v . This template is normalised such that $\sum_{i=0}^N T_i(v) = 1$ with i denoting the spectral pixels, $F_i(t)$ is the observed flux at time t . We performed the Rossiter-McLaughlin (RM, see Sect. 3.3) and systemic velocity correction outside of the *tayph*-framework, whereas the former is normally part of it.

3.1. Telluric correction and masking

We corrected for contamination by Earth’s atmosphere with the standalone version of *molecfit* (v1.5.9; Smette et al. 2015; Kausch et al. 2015), individually fitting each exposure in spectral regions dominated by water vapour and O_2 absorption. The resulting models were interpolated onto the same wavelength grid¹ as the order-by-order spectra (S2D products) and divided out. We then shifted to the stellar rest frame, where the spectral lines of the host star are stationary. This shift accounts for the

¹ Note that this included velocity corrections to account for the BERV.

stellar reflex motion induced by the orbiting planet but excludes the systemic velocity at this point, as it only introduces a constant offset. To mitigate residual features, we applied a sigma-clipping algorithm following Hoeijmakers et al. (2020b). With the spectra shifted into the stellar rest frame, we constructed transmission spectra by dividing each exposure by the out-of-transit mean stellar spectrum. We then computed the median absolute deviation within 40-pixel windows in the resulting residual (transmission) spectra and flagged all the 5σ outliers. The resulting mask was subsequently applied to the non-normalised spectra used in the cross-correlation analysis. This ensures that outlier rejection is based on the residual spectra, while preserving the noise properties and airmass dependencies of the original flux spectra during the cross-correlation step. Additionally, we masked pixels where the telluric contamination reduces the flux by more than 50% to avoid excessive noise on the cross-correlation signal. *molecfit* successfully corrects the telluric water lines around the sodium doublet (589–589.6 nm) to a level well below the pre-correction noise, with residuals typically at or below a few percent of the noise level.

3.2. Cross-correlation analysis

We performed the cross-correlation analysis for all planets in our sample with templates for Fe and Ti calculated at 3,000 K from Kitzmann et al. (2023). These templates assume an isothermal atmosphere at 3,000 K in hydrostatic and chemical equilibrium. The templates were calculated for a ‘standard’ inflated ultra-hot Jupiter with $R_p = 1.5 R_{\text{Jup}}$, and a base pressure at the bottom of the atmosphere of 10 bar. To achieve a homogeneous population study, we used the same template across all datasets even if this may result in lower detection significances for individual planets. These templates probe roughly similar pressure levels in the atmosphere; see Fig. 2. After the cross-correlation with the template over a radial velocity range from $-1,000$ to $1,000 \text{ km s}^{-1}$ in steps of 1 km s^{-1} , we divided the mean out-of-transit cross-correlation function to remove the signal from the host star. Lastly, we applied a high-pass filter with a full width at half maximum of 100 km s^{-1} to remove any residual broad-band variation.

3.3. Rossiter–McLaughlin correction

When a planet transits in front of its host star, it consecutively covers parts of the rotating stellar disc. This obscured area introduces distortions in the stellar lines, called the Rossiter–McLaughlin effect (RM; Rossiter 1924; McLaughlin 1924). We corrected for the RM effect following the method described by Prinoth et al. (2025), using the *StarRotator* code (see also Prinoth et al. 2023; Hoeijmakers et al. 2024b; Lam et al. 2024, and Hoeijmakers, in prep.). This approach models the average stellar cross-correlation function as a Gaussian centred on the systemic velocity. The Gaussian fit is shifted by the component of the stellar rotational velocity projected along the line of sight, which corresponds to the region of the stellar surface occulted by the transiting planet. The local velocity of each stellar surface element depends on the projected stellar rotational velocity, $v \sin i$, and the planet’s position on the stellar disc, which is governed by the projected orbital obliquity, λ . For a full derivation of the velocity field and model geometry, we refer to Prinoth et al. (2024). The planet-to-star radius ratio was held fixed due to its degeneracy with the amplitude and width of the stellar cross-correlation function (the Gaussian). We performed the param-

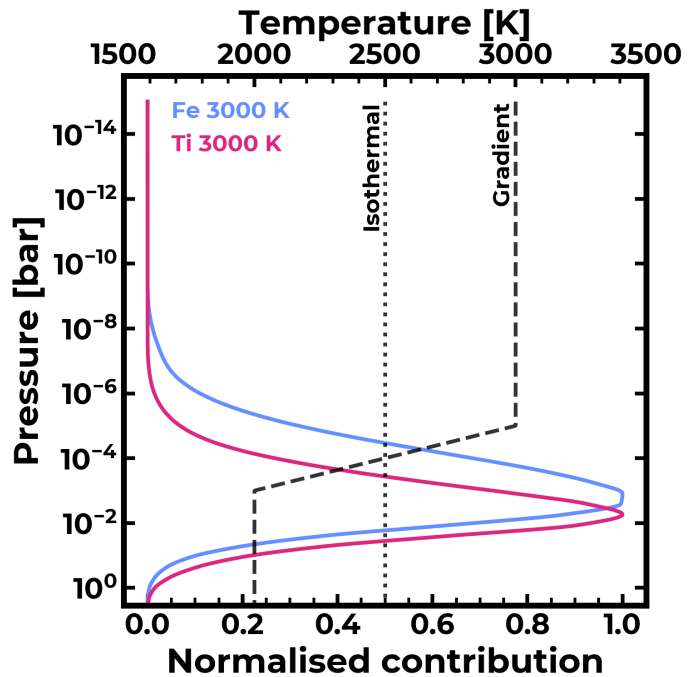


Fig. 2: Contribution functions of the cross-correlation templates and considered temperature-pressure profiles for the forward models. The Fe template probes slightly higher than the Ti template.

ter inference within a Bayesian framework using *pymultinest* (Buchner et al. 2014). For details of the implementation and a representative application, see *StarRotator* (Hoeijmakers et al. 2024b) and the full methodology in Prinoth et al. (2025).

Following the RM correction, we visually inspected the corrected cross-correlation maps for each dataset and template combination to assess the quality of the removal. In general, the RM signal was removed down to the noise level. However, in a small number of cases, individual exposures displayed significant residual structures after correction, typically associated with anomalous flux variations or poorly corrected systematics. Such exposures were excluded from the subsequent analysis to avoid introducing spurious features into the resulting cross-correlation functions. In total, no more than three exposures were excluded for any individual dataset. These exclusions occurred only for the Fe analysis, where the RM signal is strongest, while for Ti the RM contribution is weak to negligible.

3.4. Velocity correction

We measured the systemic velocity for each transit observation by fitting a rotationally broadened stellar line (Gray 2008) to the average cross-correlation function of all out-of-transit exposures. To obtain the cross-correlation signal of the star, we used a suitable PHOENIX atmosphere model (Husser et al. 2013) based on the stellar parameters for the effective temperature T_{eff} and surface gravity $\log g$ in Table B.1 as a template, broadened to the line-spread function of the instrument. The velocity shift measured for each transit was applied to align all exposures of a given time series into the true rest frame of the system. Fitting the systemic velocity for each individual time series assures that the signals are truly aligned and not caused by the relative wavelength offsets between spectrographs and dates. However, since we did not study any dynamical aspects of the sample, this ve-

locity correction has a minor impact on the fit but was performed for consistency. A detailed description of the systemic velocity fit can be found in (Seidel et al. 2026). Following the shift of the cross-correlation signal by the constant offset of the system velocity, we produced the K_p - V_{sys} maps by assuming different values for the orbital velocity K_p ranging from 0 to 400 km s⁻¹. For each of these steps (1 km s⁻¹), we shifted the spectra to this assumed planetary rest frame

$$v_{\text{planet}} = K_p \sin(2\pi\phi) \sin i + v_{\text{sys}} - v_{\text{BERV}}, \quad (2)$$

where ϕ is the orbital phase ($\phi = 0$ is the transit centre), i is the orbital inclination, v_{sys} is the systemic velocity for the given observation, and v_{BERV} is the barycentre velocity. Note that we previously corrected for v_{BERV} and v_{sys} , so they are only mentioned in Eq. (2) to showcase the rest frame of the planet with respect to the observer's rest frame. Because all these planets orbit on extremely short orbits ($P \leq 6$ days), their orbits should have had enough time to be circularised over the lifetime of the systems caused by strong tidal interactions (e.g. Hut 1981; Matsumura et al. 2010). Hence, it is also assumed that all planets orbit on circular orbits, and no eccentricity is included in Eq. (2).

3.5. Model prediction and comparison

For each planet with a Fe and/or Ti detection ($\geq 5\sigma$), we generated a suite of forward-model transmission spectra using petitRADTRANS v2 (Mollière et al. 2019), based on the planetary and stellar parameters listed in Table B.1. Atomic line opacities for Fe and Ti were taken from the VALD3 database (Ryabchikova et al. 2015), and continuum opacity sources included collision-induced absorption from H₂-H₂ (Borysow et al. 2001; Borysow 2002) and H₂-He (Borysow et al. 1988), bound-free and free-free absorption from H⁻ (Gray 2008), and Rayleigh scattering by H₂ (Dalgarno & Williams 1962) and He (Chan & Dalgarno 1965).

We assumed the atmospheres to be 1D and in hydrostatic and chemical equilibrium. Two temperature–pressure prescriptions were considered to capture plausible thermal structures probed via transmission spectroscopy. In the first scenario ('isothermal'), the atmosphere was held at a constant temperature T , varied from 2,000 to 4,000 K in 200 K steps. In the second scenario ('gradient'), a simplified inverted profile was adopted in which temperature varies linearly with log-pressure between 10⁻⁵ and 10⁻³ bar (as adopted on the daysides of ultra-hot Jupiters; e.g. Bonidie et al. 2026, see their Fig. 7), transitioning from $T + 500$ K at low pressures to $T - 500$ K at higher pressures and remaining isothermal outside this range. These scenarios bracket a range of plausible upper-atmosphere temperature structures. Example T–p profiles for $T = 2,500$ K are shown in Fig. 2.

Based on these T–p profiles, we computed the equilibrium volume-mixing ratios using FastChem Cond (Stock et al. 2018, 2022; Kitzmann et al. 2024), including condensation via the rain-out prescription from Marley et al. (2013). To explore the impact of elemental abundance variations, Fe and Ti abundances were scaled by factors 1 (nominal), 10⁻¹, and 10⁻² relative to stellar metallicity (see Table B.1) prior to equilibrium calculations.

We injected these forward models into the observed time-series data at the expected projected orbital velocity $K_p = \frac{2\pi a}{P} \sin i$ and systemic velocity v_{sys} following the methodology described in Hoeijmakers et al. (2020a) and subsequent studies (e.g. Prinoth et al. 2023; Hoeijmakers et al. 2024a). We then performed the same cross-correlation analysis as in

Sect. 3.2 on the dataset including the injected forward models, yielding the recovered cross-correlation amplitudes expected for each temperature and abundance scenario under the same observational conditions as the actual data.

3.6. Cross-correlation metric $\Delta_{\text{Ti-Fe}}$

To quantify the relative trend of Ti and Fe while minimising system-dependent effects, we defined a logarithmic depletion metric based on the recovered cross-correlation amplitudes. Absolute signal strengths depend strongly on factors such as planetary radius, surface gravity, atmospheric scale height, stellar brightness, signal-to-noise ratio, and instrumental systematics, making direct comparisons across different planets or instruments unreliable.

By adopting the ratio of Ti to Fe signals within the same dataset, many of these shared dependencies largely cancel out. To place all planets on a common scale, this ratio was further normalised by a fixed reference value derived from isothermal model spectra at 2,600 K. The metric $\Delta_{\text{Ti-Fe}}$ is thus defined as

$$\Delta_{\text{Ti-Fe}} = \log_{10} \left(\frac{S_{\text{Ti,obs}}}{S_{\text{Fe,obs}}} \right) - \log_{10} \left(\frac{S_{\text{Ti,ref at 2600 K}}}{S_{\text{Fe,ref at 2600 K}}} \right), \quad (3)$$

where $S_{X,\text{obs}}$ denotes the observed cross-correlation peak amplitude for species X ($X \in [\text{Fe}, \text{Ti}]$).

The 2,600 K reference does not represent the atmospheric temperature of any individual planet but rather defines a fixed baseline used consistently throughout the analysis. Importantly, the same reference was adopted for all temperature–pressure prescriptions considered in this work, including both isothermal and temperature-gradient models. In practice, all forward-model spectra, irrespective of their temperature structure, were projected onto the same fixed reference template at 2,600 K when computing $\Delta_{\text{Ti-Fe}}$. This ensured that all measurements and model predictions were evaluated relative to the same baseline and that differences in atmospheric structure affected only the recovered signal amplitudes themselves rather than the definition of the normalisation.

The choice of 2,600 K was motivated by the fact that Ti and Fe are expected to exhibit broadly similar behaviour in this regime, with minimal contributions from ionisation effects and TiO formation at the pressures probed (see Fig. 2), thereby providing a stable anchoring point for the comparison. The metric should therefore be interpreted as a relative deviation with respect to a single fiducial model reference point rather than as a per-planet equilibrium chemistry residual. While injected models are planet-specific, all cross-correlations were computed using the same templates (see Sect. 3.2), ensuring a homogeneous basis for the population-level analysis.

To compare the observed trends with model predictions, we evaluated the same metric on the forward models by replacing $S_{X,\text{obs}}$ with the corresponding cross-correlation strengths recovered from the injected signals. This yields the predicted values of $\Delta_{\text{Ti-Fe}}$ for both isothermal and temperature-gradient models across a range of atmospheric temperatures (2,000–4,000 K) and elemental abundance scalings (1, 10⁻¹, 10⁻²) for each planet.

4. Results and discussion

4.1. Detections and population-level trend of Fe and Ti

We performed a homogeneous high-resolution cross-correlation analysis of neutral iron and titanium across a sample of ten hot

and ultra-hot Jupiters. We detect Fe at high significance ($> 5\sigma$) in seven planets (WASP-76 b, KELT-20 b, WASP-121 b, WASP-178 b, TOI-1518 b, HAT-P-70 b and WASP-189 b), while Ti is detected in only four (WASP-121 b, TOI-1518 b, HAT-P-70 b and WASP-189 b; see Figs. A.1 and A.2). Iron therefore appears ubiquitous in all planets in our sample with $T_{\text{eq}} \gtrsim 2200$ K, whereas titanium is only detected in a subset of the hottest ($T_{\text{eq}} \gtrsim 2350$ K) planets. Although all reported species have previously been detected in the literature (e.g. Ehrenreich et al. 2020; Stangret et al. 2020; Bello-Arufe et al. 2022b; Prinoth et al. 2022; Damasceno et al. 2024; Simonnin et al. 2025; Prinoth et al. 2025; Sun et al. 2026), our uniform analysis enables a direct and unbiased comparison of their relative trend across the population.

No significant detections are found for KELT-11 b, WASP-172 b, and WASP-173 A b. The comparatively low equilibrium temperature of KELT-11 b ($T_{\text{eq}} \sim 1,700$ K) likely suppresses neutral atomic species, while the higher surface gravity of WASP-173 A b reduces its atmospheric scale height and thus the strength of transmission signatures. WASP-172 b does show a tentative Fe signal (Seidel & Prinoth et al. 2023), although it remains below the detection threshold in our re-analysis. These cooler planets ($T_{\text{eq}} \lesssim 2,000$ K) probe the regime near the expected condensation boundaries of refractory elements and therefore provide important constraints on their removal from the gas phase. Our non-detections of Ti on WASP-178 b is likely due to the lower data quality and overlap of the RM with the planetary trace in these data, as discussed in Damasceno et al. (2024) and evidenced by the weaker observed Fe signal (Fig. A.1). Indeed, given its equilibrium temperature between those of WASP-121 b and TOI-1518 b, both of which show Ti detections, we expect Ti to also be present in the gas phase on WASP-178 b. However, more observations will be needed to confirm this.

To quantify the trend across the sample, we used the cross-correlation metric $\Delta_{\text{Ti-Fe}}$ (Eq. 3), which measures the Ti-to-Fe signal ratio relative to a reference model and largely removes system-dependent observational effects. The $\Delta_{\text{Ti-Fe}}$ measured across our sample exhibits a clear decrease towards lower equilibrium temperatures (Fig. 3). While Fe remains detectable across most of the temperature range, Ti absorption declines rapidly below $T_{\text{eq}} \sim 2,200 - 2,400$ K.

This population-level trend demonstrates that titanium is systematically removed from the observable atomic phase at higher temperatures than iron. This trend is consistent with previous retrieval studies (e.g. Gandhi et al. 2023; Maguire et al. 2023; Pelletier et al. 2023, 2026; Prinoth et al. 2025), which report Ti abundances depleted by $\log(X/X_{\star}) \sim -1$ or more, while Fe remains close to stellar values.

4.2. Constraints from forward models

To interpret this observed population trend, we compared the measured values of $\Delta_{\text{Ti-Fe}}$ to predictions from a suite of forward models (see Sect. 3.5). Figure 4 shows the model predictions averaged over all planets at each temperature. The small scatter between individual planets (captured in the 84th percentile region) demonstrates that $\Delta_{\text{Ti-Fe}}$ effectively removes most system-dependent effects, enabling a direct comparison between models and observations.

The isothermal models predict only a weak dependence of $\Delta_{\text{Ti-Fe}}$ on temperature across the parameter space probed by our sample. At higher temperatures, $\Delta_{\text{Ti-Fe}}$ decreases due to the onset of ionisation beyond 2,600 K, which preferentially reduces the neutral Ti signal because of its lower ionisation energy rel-

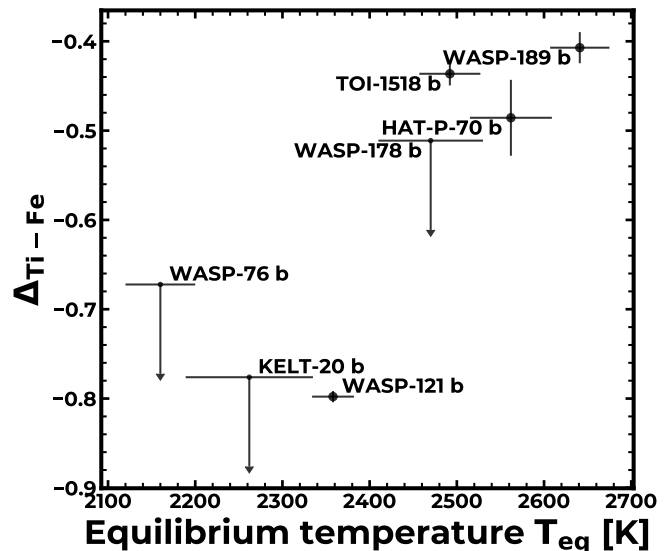


Fig. 3: Observed $\Delta_{\text{Ti-Fe}}$ across the sub-sample of the population with Fe and/or Ti detections. The $\Delta_{\text{Ti-Fe}}$ shows a clear downward trend towards colder equilibrium temperatures, indicating that the degree to which Ti is weaker than Fe compared to model prediction is more severe on colder planets. The uncertainties of the observed $\Delta_{\text{Ti-Fe}}$ are computed via Gaussian error propagation of the fitted peak of the cross-correlation map in Eq. (3).

ative to Fe (e.g. Prinoth et al. 2023). At lower temperatures, however, $\Delta_{\text{Ti-Fe}}$ remains nearly constant. Although Ti is partially converted into TiO, this transition occurs gradually over a broad pressure range, leaving a substantial fraction of atomic Ti distributed across the atmosphere (see Fig. C.1). As a result, the observable Ti signal is only weakly affected, and isothermal atmospheres cannot reproduce the strong decline in Ti relative to Fe observed across the population under the assumption of uniform Ti depletion.

Thus, reproducing the observed trend with isothermal models requires invoking a temperature-dependent depletion of titanium, with cooler planets exhibiting progressively stronger depletion relative to Fe. This scenario naturally points towards cold-trapping processes that become more efficient at lower equilibrium temperatures, for example through enhanced condensation of Ti-bearing species on the nightside (Parmentier et al. 2013). In this picture, the observed population trend directly reflects a temperature-dependent removal of Ti from the atmosphere.

In contrast, models including a temperature gradient reproduce the observed trend without requiring a temperature-dependent depletion. These models produce a rapid decline in $\Delta_{\text{Ti-Fe}}$ over a narrow temperature range and therefore provide a much better match to the data. In such atmospheres, temperatures decrease with increasing pressure over the region probed by the cross-correlation templates. Because the Ti template probes slightly deeper atmospheric layers than Fe (see Fig. 2), it becomes more sensitive to cooler regions of the atmosphere. In these deeper layers, Ti is efficiently converted into TiO and subsequently removed from the gas phase through condensation (e.g. into Ti-bearing condensates such as CaTiO_3). This process both depletes the available Ti budget more significantly compared to Fe (see Fig. C.1) and confines the remaining atomic Ti to a narrow region. This differential response naturally produces

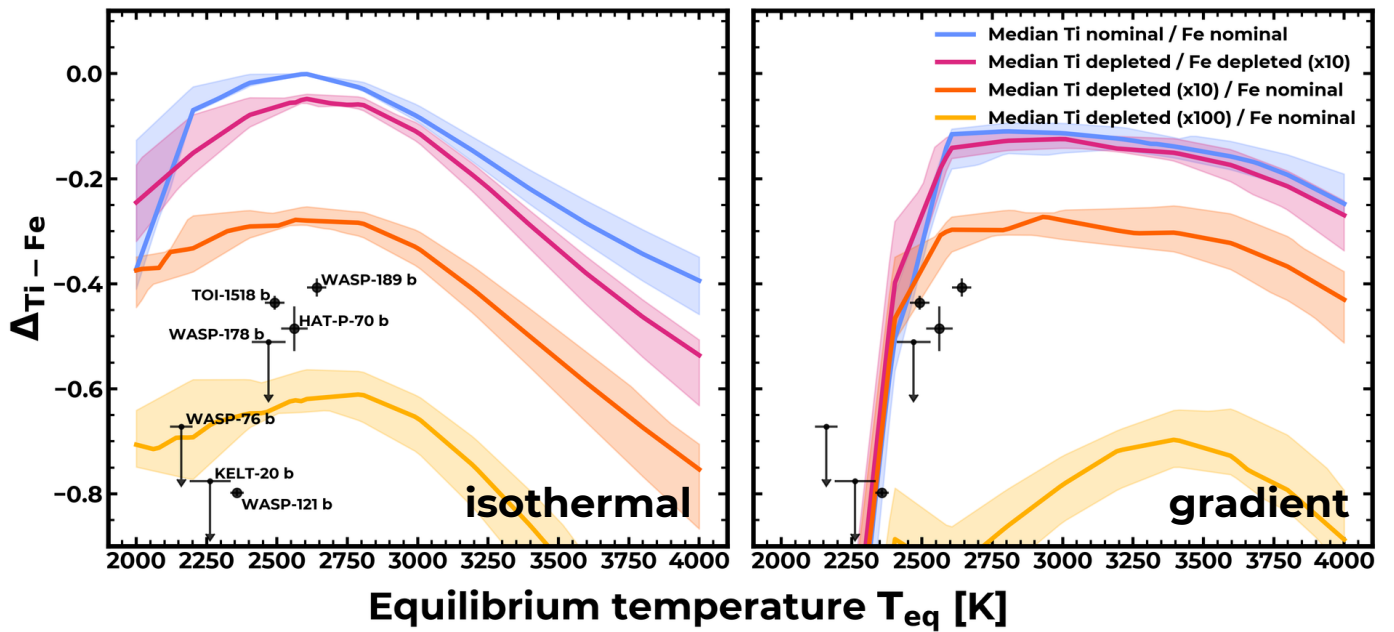


Fig. 4: Model comparison for isothermal (left) and gradient (right) models. The upper limits correspond to 3σ limits based on the noise in the cross-correlation map. The model medians were computed by evaluating the models in Eq. (3) for all planets. The shaded regions indicate the 84th percentiles, demonstrating that this metric effectively cancels out any major planet-specific dependencies. Consequently, the overall trend of the metric is captured by all models together.

the observed decline in $\Delta_{\text{Ti-Fe}}$.

At lower temperatures, the gradient models become increasingly insensitive to the overall Ti abundance. In this regime, most Ti is already efficiently recombined into TiO (or rained out completely), and the residual atomic Ti signal is primarily set by the local chemical balance rather than the total Ti inventory, making it difficult to distinguish between nominal and depleted abundances. In contrast, the hottest planets in our sample suggest that Ti is globally depleted relative to Fe by roughly an order of magnitude. This finding disfavors a purely temperature-dependent depletion scenario and instead points towards an overall depletion of Ti relative to Fe across the population.

4.3. Breaking degeneracies and future prospects

Distinguishing between intrinsic abundance variations and atmospheric processes such as cold trapping requires additional observational constraints.

One complementary avenue is the detection of TiO in planets with equilibrium temperatures of $\sim 2,000$ – $2,500$ K, where TiO formation is expected to be efficient. In this regime, an anti-correlation between atomic Ti and molecular TiO would provide a direct signature of chemical partitioning. However, current limitations in TiO line lists may complicate or even prevent such measurements, except for the most favourable planets (Hoeijmakers et al. 2015; McKemmish et al. 2019; Prinoth et al. 2022). Ground-based observations are particularly affected by inaccuracies in these line lists, whereas space-based observations are less sensitive to such issues because they do not resolve the dense forest of individual spectral lines, which makes them prone to being confused with other species or even reflected light (Pelletier et al. 2026).

Extending the sample to higher equilibrium temperatures provides a complementary test. If the observed trend is primarily driven by TiO formation and condensation associated with

temperature gradients, $\Delta_{\text{Ti-Fe}}$ should flatten at sufficiently high temperatures, where titanium remains predominantly atomic (as suggested by Fig. 4). At the same time, however, ionisation becomes significant and may further reduce the observable neutral Ti abundance. Nonetheless, exploring higher temperatures should help confirm or rule out (partial and/or temperature-dependent) cold trapping as the underlying cause. Testing this region of the parameter space would also clarify whether these planets follow the predicted overall depletion in Ti/Fe.

Finally, high-resolution emission spectroscopy probes deeper and hotter atmospheric layers than transmission spectroscopy and is more sensitive to the temperature–pressure structure. Joint transmission and emission measurements of the same planets would provide a powerful means of disentangling vertical structure effects from global abundance variations. Together, these observations will be essential for establishing a comprehensive picture of refractory element chemistry in strongly irradiated exoplanet atmospheres.

5. Conclusions

We presented a homogeneous high-resolution spectroscopic analysis of iron and titanium absorption in ten hot and ultra-hot Jupiter atmospheres observed with ESPRESSO and MAROON-X. Using a consistent methodology and the relative cross-correlation metric $\Delta_{\text{Ti-Fe}}$, we directly compared the observed trend of these species across a critical temperature range for refractory chemistry. We identified a clear population-level trend in which $\Delta_{\text{Ti-Fe}}$ declines rapidly towards lower equilibrium temperatures.

Forward-model comparisons indicate that reproducing this trend requires one of two scenarios. First, assuming isothermal temperature-pressure profiles, Ti is progressively depleted relative to Fe in cooler planets, consistent with selective cold-trapping processes. In this case, the hottest planets show little,

while the coldest planets exhibit the strongest Ti depletion. Second, invoking non-isothermal profiles with atmospheric temperature gradients leads to efficient conversion of Ti into TiO in deeper layers, followed by condensation into Ti-bearing species, which removes Ti from the observable atmosphere. While this scenario naturally reproduces the observed trend, the hottest planets still indicate an additional overall Ti depletion by roughly a factor of 10 relative to Fe, which cannot be explained by this mechanism alone. These findings suggest that molecular partitioning, ionisation, condensation, and cold-trapping processes collectively shape the observable refractory chemistry of ultra-hot Jupiter atmospheres.

Although current observations cannot fully distinguish between these scenarios, expanding homogeneous high-resolution surveys to larger and more diverse samples will be crucial. This includes planets orbiting fainter host stars, which will become accessible with high-resolution spectrographs on the Extremely Large Telescope or using ESPRESSO's 4UT mode (e.g. [Borsa et al. 2021](#); [Seidel et al. 2025](#); [Prinoth et al. 2025](#); [Vaughan et al. 2026](#)), or more challenging host stars ([Jiang et al. 2026](#), e.g. active stars or pulsators). Such efforts will be key to breaking these degeneracies and achieving a comprehensive understanding of refractory element chemistry in strongly irradiated giant planets.

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Appendix A: Detection maps

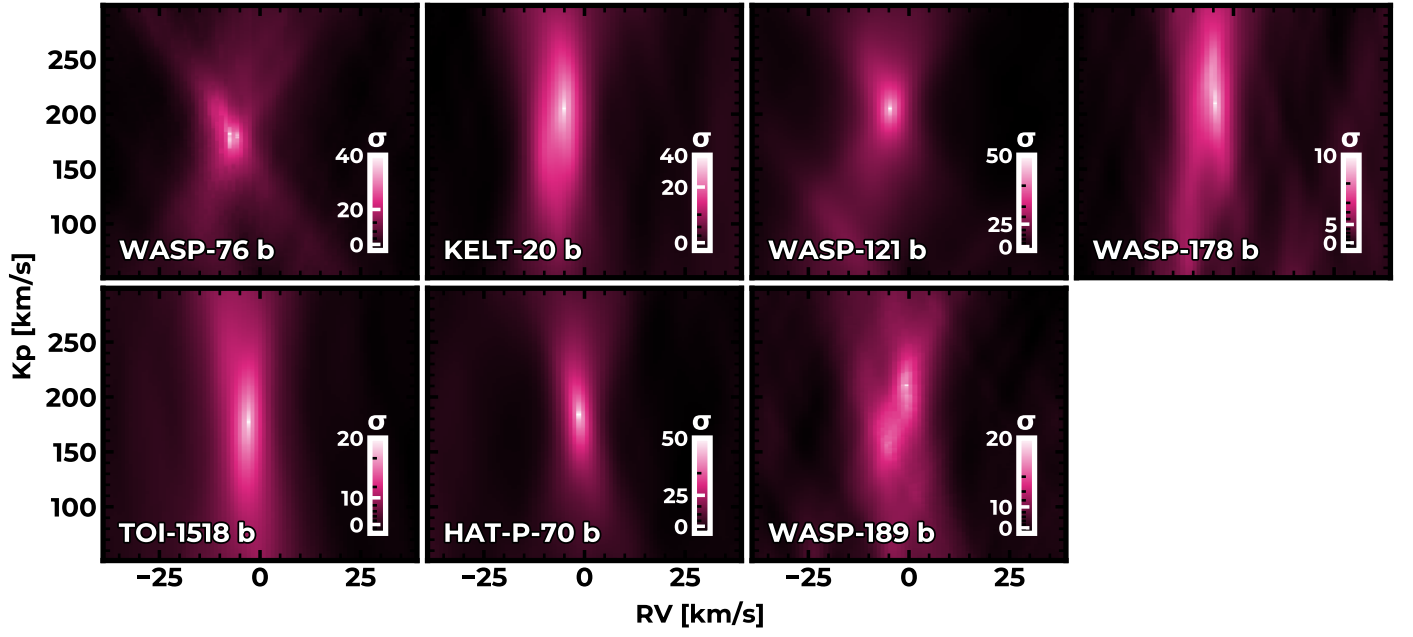


Fig. A.1: K_p - V_{sys} diagrams showing detected Fe absorption in the sample. Each panel displays the stacked K_p - V_{sys} diagram after correcting individual observations for their system velocities. The colour bars indicate the detection significance, calculated by dividing the diagram by its standard deviation outside the velocity ranges affected by the star, planet, Rossiter–McLaughlin effect, and tellurics.

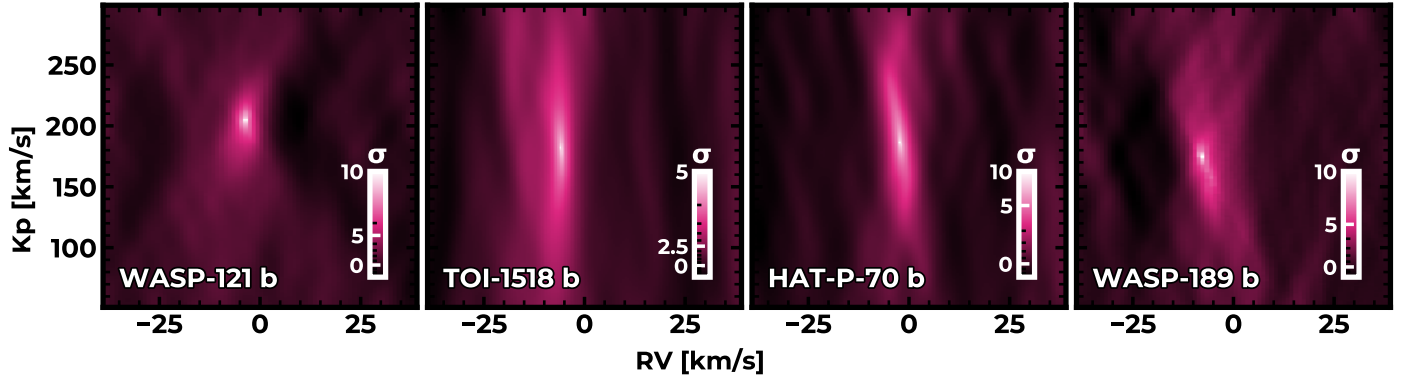


Fig. A.2: Same as Fig. A.1 but for Ti.

Appendix B: Stellar and planetary parameters for forward models

Table B.1: Overview of the stellar and planetary parameters adopted in this study.

	WASP-76 b	KELT-20 b	WASP-121 b	WASP-178 b	TOI-1518 b	HAT-P-70 b	WASP-189 b
Stellar parameters							
T_{eff} [K]	6329 ± 65	8720^{+250}_{-260}	6459 ± 140	9360 ± 150	7299^{+98}_{-100}	8450^{+540}_{-690}	8000 ± 80
$\log g$ [cgs]	4.196 ± 0.106	$4.290^{+0.017}_{-0.020}$	$4.242^{+0.011}_{-0.012}$	4.31 ± 0.04	4.136 ± 0.011	$4.181^{+0.055}_{-0.063}$	3.9 ± 0.2
R_s [$R_\odot$]	1.756 ± 0.071	$1.565^{+0.057}_{-0.064}$	1.458 ± 0.030	1.67 ± 0.07	1.942 ± 0.043	$1.858^{+0.119}_{-0.091}$	2.36 ± 0.03
Metallicity [Fe/H]	0.366 ± 0.053	$-0.29^{+0.22}_{-0.36}$	0.13 ± 0.09	0.21 ± 0.16	-0.10 ± 0.12	$-0.0590^{+0.0750}_{-0.0880}$	0.29 ± 0.13
Planetary parameters							
R_p [R_{Jup}]	$1.854^{+0.077}_{-0.076}$	$1.741^{+0.069}_{-0.074}$	1.753 ± 0.036	1.81 ± 0.09	1.878 ± 0.042	$1.87^{+0.15}_{-0.10}$	1.619 ± 0.021
M_p [M_{Jup}]	$0.894^{+0.014}_{-0.013}$	≤ 3.382	1.157 ± 0.070	1.66 ± 0.12	1.83 ± 0.47	≤ 6.78	$1.99^{+0.16}_{-0.14}$
$\log g_p$ [cm g^{-2}]	2.809 ± 0.037	≤ 3.44	2.97 ± 0.03	3.10 ± 0.05	3.11 ± 0.11	≤ 3.68	3.38 ± 0.03
T_{eq} [K]	2160 ± 40	2262 ± 73	2358 ± 52	2470 ± 60	2492 ± 38	2562^{+43}_{-52}	2641 ± 34
References	Ehrenreich et al. (2020)	Lund et al. (2017)	Delrez et al. (2016)	Hellier et al. (2019)	Simonnin et al. (2025)	Zhou et al. (2019)	Lendl et al. (2020)
	West et al. (2016)		Bourrier et al. (2020)		Cabot et al. (2021)		Anderson et al. (2018)

Notes: The surface gravity $\log g_p$ of the planet is calculated based on the mass and radius, assuming Gaussian error propagation.

Appendix C: Volume mixing ratios

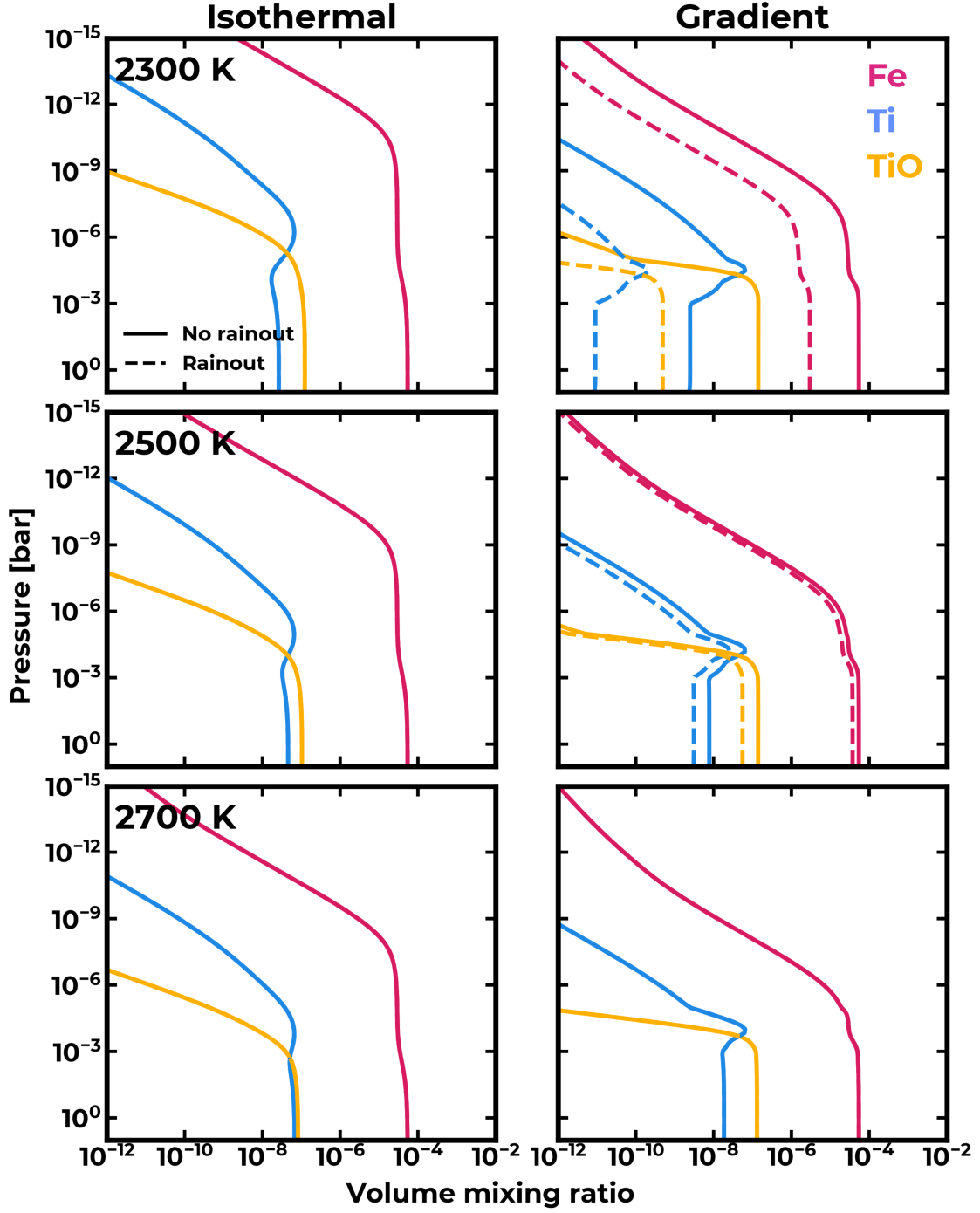


Fig. C.1: Volume mixing ratios of Fe (blue), Ti (pink), and TiO (yellow) for isothermal (left) and non-isothermal (right) atmospheres at 2,300 K (top), 2,500 K (middle), and 2,700 K (bottom). Solid and dashed lines indicate models without and with rainout, respectively. In the isothermal case, rainout is not effectively triggered despite being included, and the gas-phase Ti abundance is primarily governed by partitioning between atomic Ti, TiO, and ionised Ti. As a result, Ti remains distributed over a broad pressure range, leading to only modest changes in its observable signal. In contrast, the non-isothermal atmospheres develop cooler layers at depth where Ti is efficiently converted into TiO and subsequently removed through condensation (e.g. into CaTiO_3). This process depletes the available gas-phase Ti and confines the remaining atomic Ti to a narrower region at low pressures. While Fe also begins to condense at depth, it is less strongly affected over the pressures probed by the observations. Because the Ti signal is more sensitive to deeper atmospheric layers than Fe, this differential depletion leads to a pronounced suppression of the Ti signal relative to Fe, naturally explaining the strong decrease in $\Delta_{\text{Ti-Fe}}$ for atmospheres with temperature gradients.

Appendix D: Observations

Table D.1: Overview of the observations considered in this study.

Planet	Date	Instrument	PI, #	S/N ^a	T _{eq} [K]	Atmospheric detections in ^b
KELT-11 b	2024-03-31	MAROON-X	Parmentier, GN-2024A-Q-130	22.2-302.5	1712	
	2024-04-19	MAROON-X	Parmentier, GN-2024A-Q-130	22.2-297.6		
WASP-172 b	2022-06-01	ESPRESSO	Albrecht, 109.22Z4.006	14.3-63.3	1740	Seidel & Prinoth et al. (2023)
KELT-4 A b	2023-12-07	MAROON-X	Parmentier, GN-2023B-Q-127	28.0-82.7	1827	
	2023-12-10	MAROON-X	Parmentier, GN-2023B-Q-127	26.4-77.6		
	2023-12-16	MAROON-X	Parmentier, GN-2023B-Q-127	24.7-76.3		
	2023-12-31	MAROON-X	Parmentier, GN-2023B-Q-127	-		
WASP-173A b	2022-07-24	ESPRESSO	Albrecht, 109.22Z4.003	12.4-54.9	1880	Jiang et al. (2026), non-detection
KELT-7 b	2023-12-28	MAROON-X	Parmentier, GN-2023B-Q-127	22.2-158.1	2048	
WASP-19 b	2019-01-14	ESPRESSO	Sedaghati, 0102.C-0311	13.2-60.7	2077	Sedaghati et al. (2021)
	2019-03-03	ESPRESSO	Sedaghati, 0102.C-0311	11.8-56.1		Sedaghati et al. (2021)
	2019-03-22	ESPRESSO	Sedaghati, 0102.C-0311	13.0-66.3		Sedaghati et al. (2021)
	2020-01-11	ESPRESSO	Sedaghati, 0102.C-0311	6.8-48.9		Sedaghati et al. (2021)
KELT-17 b	2020-12-25	ESPRESSO	Seidel, 0106.C-0126	22.7-107.2	2087	
	2021-01-31	ESPRESSO	Seidel, 0106.C-0126	32.0-134.9		
	2021-03-06	ESPRESSO	Seidel, 0106.C-0126	25.5-111.4		
WASP-76 b	2018-09-02	ESPRESSO	Pepe, 1102.C-0744	13.1-83.7	2228	Ehrenreich et al. (2020)
	2018-10-30	ESPRESSO	Pepe, 1102.C-0744	10.5-67.5		Ehrenreich et al. (2020)
	2019-10-18	ESPRESSO	Gibson, 0104.C-0642	29-55		Maguire et al. (2024)
	2020-09-03	MAROON-X	Pelletier, GN-2020B-Q-122	20.0-68.4		Pelletier et al. (2023)
	2020-09-12	MAROON-X	Pelletier, GN-2020B-Q-122	17.6-63.1		Pelletier et al. (2023)
	2021-10-28	MAROON-X	Debras, GN-2021B-Q-138	29.4-99.0		Pelletier et al. (2023)
KELT-20 b	2023-07-07	MAROON-X	Parmentier, GN-2023A-Q-224	71.3-190.6	2263	De Lia et al. (2026)
WASP-121 b	2021-01-26	ESPRESSO	Gibson, 0106.C-0516	27-37	2338	Maguire et al. (2024)
	2021-03-04	ESPRESSO	Gibson, 0106.C-0516	21-36		Maguire et al. (2024)
	2019-01-06	ESPRESSO	Pepe, 1102.C-0744	21-36		Borsa et al. (2021)
	2018-11-30	ESPR-4UT	60.A-9128 (Comm.)	23.1-163.3	2358	Borsa et al. (2021)
	2023-09-23	ESPR-4UT	Seidel, 111.24J8	26.6-174.5		Seidel et al. (2025)
MASCARA-4 b	2020-02-12	ESPRESSO	Wytttenbach, 0104.C-0605 300	44.9-201.7	2405	Zhang et al. (2022)
	2020-02-29	ESPRESSO	Wytttenbach, 0104.C-0605	46.3-207.6		Zhang et al. (2022)
WASP-178 b	2021-05-03	ESPRESSO	Pepe, 1104.C-0350	11.3-48.6	2470	Damasceno et al. (2024)
	2021-07-09	ESPRESSO	Pepe, 1104.C-0350	9.3-37.7		Damasceno et al. (2024)
TOI-1518 b	2022-08-13	MAROON-X	Parmentier, GN-2022B-Q-128	23.4-64.9	2491	Simonnin et al. (2025)
	2023-10-19	MAROON-X	Parmentier, GN-2023B-Q-127	27.4-80.2		Simonnin et al. (2025)
	2024-06-26	MAROON-X	Parmentier, GN-2024A-Q-130	24.0-65.1		Simonnin et al. (2025)
HAT-P-70 b	2023-12-13	MAROON-X	Pelletier, GN-2023B-Q-126	22.2-64.8	2559	Sun et al. (2026)
	2023-12-24	MAROON-X	Pelletier, GN-2023B-Q-126	22.2-72.5		Sun et al. (2026)
WASP-189 b	2021-06-04	ESPRESSO	Prinoth, 107.22QF	107.7-432.6	2638	Prinoth et al. (2023)
	2022-04-03	MAROON-X	Pelletier, GN-2022A-FT-208	84.1-231.6		Prinoth et al. (2024)
	2022-06-02	MAROON-X	Pelletier, GN-2022A-FT-208	84.7-233.5		Prinoth et al. (2024)

Notes: ^(a) Minimum and maximum S/N values across the full wavelength range, assuming the photon-noise limit. ^(b) First publication of the exoplanet's atmosphere from the specific dataset.