High-Resolution Spectroscopy and GCM Simulations with Magnetic Effects: Ti and Fe in the Atmosphere of TOI-2109b

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Introduction

Ultra-hot Jupiters like TOI-2109b (Wong 2021) —the second-hottest known exoplanet—are natural laboratories for studying extreme atmospheric physics. We present new high-resolution emission spectroscopy of TOI-2109b from the Gemini High resolution Optical SpecTrograph (GHOST) (Ireland et al. 2012, 2014; McConnachie et al. 2022a,b, 2024; Kalari et al. 2025) at Gemini South Observatory. This work is intended to detect key atomic species in its dayside atmosphere, providing crucial insights into the chemical composition and dynamics of this extreme exoplanet.

Observations & Target

Table 1. Planetary system parameters used in this work.

Parameter	Symbol [unit]	Value	References
Orbital Period	P [days]	$0.67247414 \pm 0.00000028$	I. Wong (2021)
Planetary Mass	M_p [M_J]	5.02 ± 0.75	I. Wong (2021)
Planetary Radius	R_p [R_J]	1.347 ± 0.047	I. Wong (2021)
Equilibrium Temp	T_{eq} [K]	3646 ± 88	I. Wong (2021)
Stellar Temp	T_* [K]	6530^{+160}_{-180}	I. Wong (2021)
Stellar Radius	R_* [$R_\odot$]	1.698 ± 0.06	I. Wong (2021)

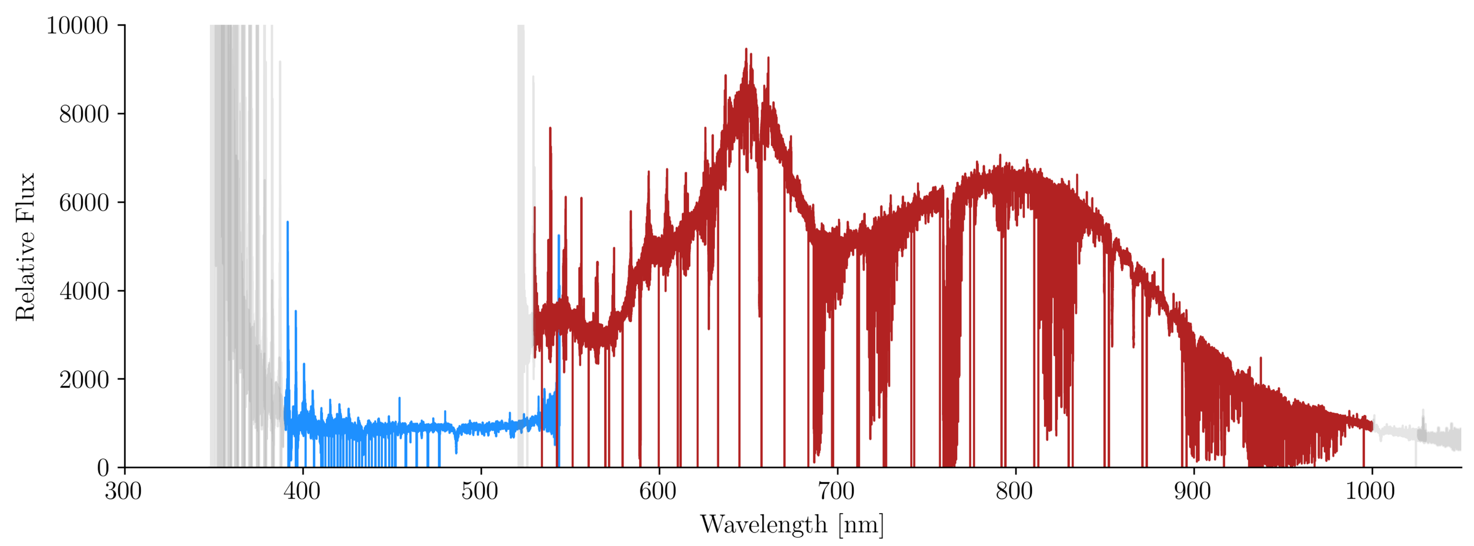

Figure 1. Example GHOST spectrum after standard reduction using the GHOST Data Reduction Software but before any additional processing applied for this work. The blue and red arms of the spectrograph are shown in blue and red, respectively, with grey regions marking wavelengths excluded from our analysis.

GHOST Observations

- **Date (UT):** 25 May 2023
- **Number of Exposures:** 70
- **Exposure Time:** 120 s
- **Orbital Phase Coverage:** 0.27 - 0.44
- **Instrument Mode:** High-resolution (R ~ 76,000)
- **Wavelength Range:** 383 - 1000 nm

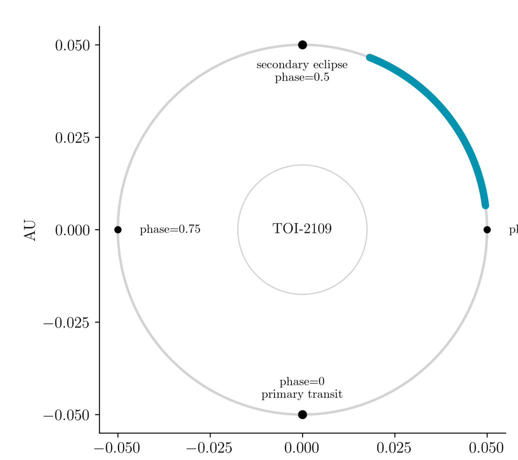

Figure 2. Visualization of the pre-eclipse orbital phases (~0.27–0.44) covered by these observations. The planetary orbit and host star are shown to scale.

Data Reduction

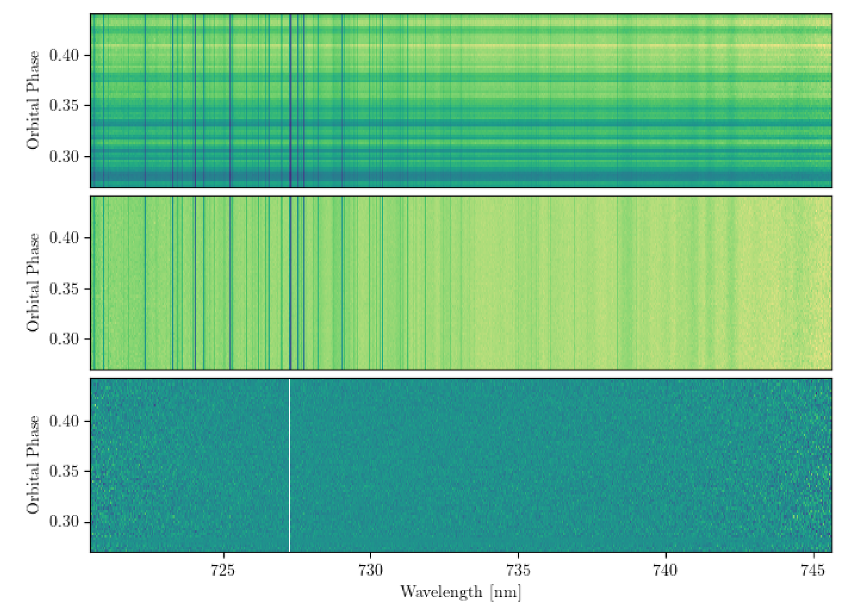

Figure 3. Results after applying the SysRem algorithm to the 14th order, using four iterations. Most major absorption features have been effectively removed, while the planetary signal remains buried within the noise.

- **Initial Processing:** Data was reduced using the GHOST DRAGONS pipeline Labrie et al. 2019, 2022), for standard calibration and extraction.
- **Sky Subtraction Barycentric Correction:** These steps were intentionally disabled to keep the data in the telluric frame.
- **Systematic Removal:** The SysRem algorithm (Tamuz 2005) was applied to remove dominant telluric and stellar absorption lines.
- **Optimization:** The optimal number of SysRem iterations was found by injecting and recovering a model signal using the Delta Cross-Correlation Function. (ΔCCF Cheverall 2023)

Analysis: Doppler Cross Correlation

We used the Doppler cross-correlation technique (e.g., Snellen et al. 2010) to search for the Doppler-shifted spectral signature of the planet as it orbits the star.

- **Atmospheric Models:** High-resolution model spectra were generated using petitRADTRANS (Molliere et al. 2019) for a suite of atomic and ionic species expected in UHJ atmospheres (Fe, Fe+, Ti, V, Mg, etc.), assuming chemical equilibrium.
- **Cross-Correlation:** Each model was shifted across a grid of radial velocities (RV) and orbital velocities (Kp) and correlated with the processed spectra.
- **Detection:** A true atmospheric signal appears as a significant peak in the resulting 2D Kp-RV map at the expected planet's orbital velocity (Kp) and RV ≈ 0 km/s (stellar rest frame).

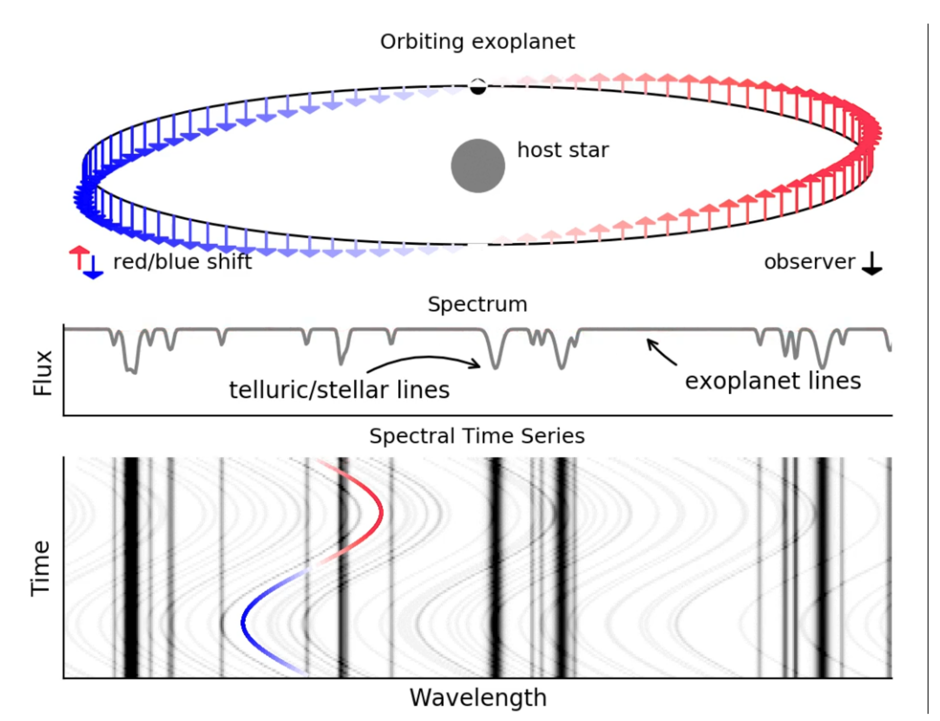

Figure 4. Illustration by Lennart van Sluijs showing how Doppler cross-correlation analysis isolates the planet's atmospheric signal from high-resolution spectra.

Preliminary Results & Ongoing Analysis

Our initial analysis is targeting atomic species Iron(Fe) and Titanium (Ti) predicted to be strong emitters in ultra-hot Jupiter atmospheres.

Conduct an injection-recovery test by injecting atmospheric models into the data and using Doppler cross-correlation to determine detection limits for non-detections.

An initial search for Iron (Fe) did not yield a significant detection, which contrasts with other findings. However, a tentative detection of Titanium (Ti) was made.

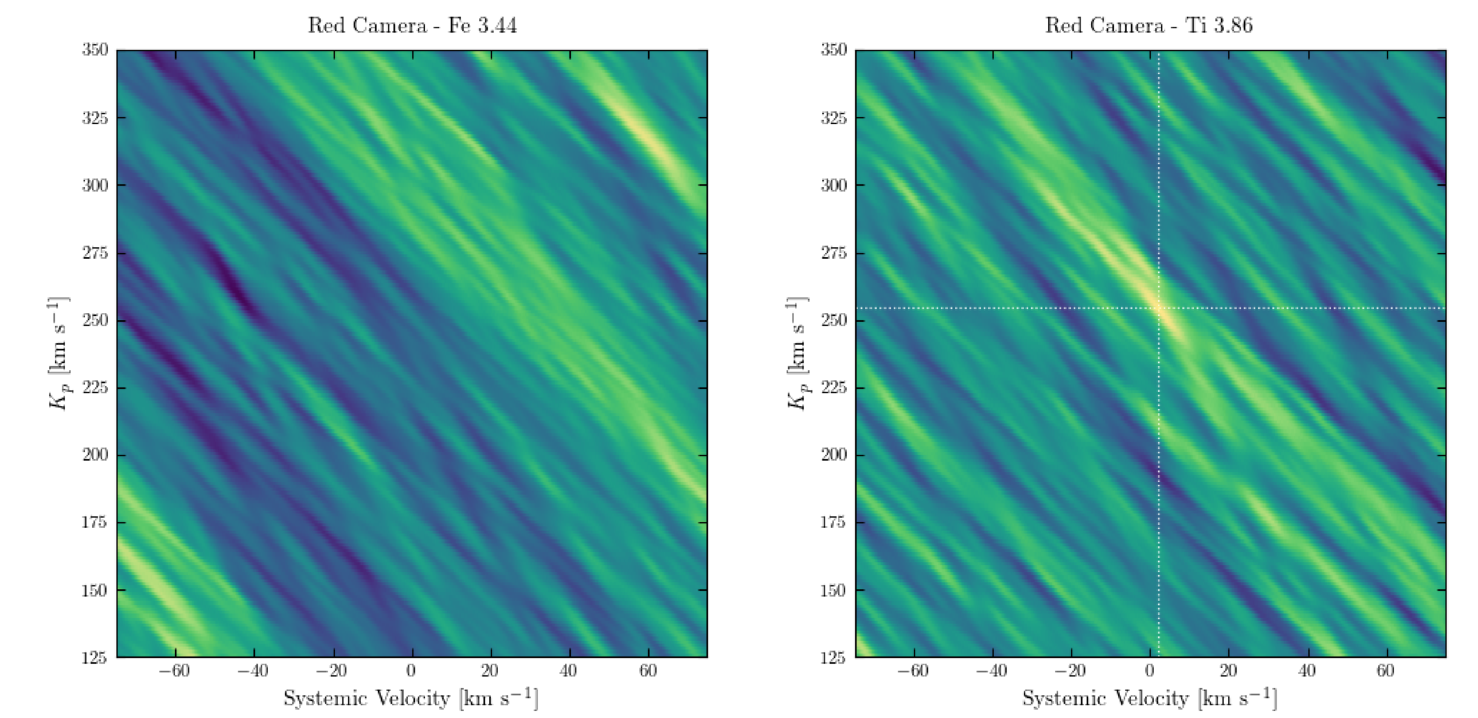

Figure 5. Cross-correlation maps using atmospheric Fe (left panel) and Ti (right panel) models. The Fe map shows no detection near the expected orbital parameters, while the Ti map reveals a clear feature at the planet's velocity, suggesting a possible Ti detection.

Next Steps and Future Work

Following atmospheric retrievals for multiple chemical species, we find promising evidence for titanium (Ti) in the atmosphere of TOI-2109 b. However, our data show no significant detection of iron (Fe). The non-detection of Fe, despite data of sufficient quality for such a detection, introduces a new question regarding the presence or abundance of iron in this planet's atmosphere.

New: In collaboration with **Dr. Hayley Beltz**, we are now developing **General Circulation Models (GCMs)** that include **magnetic effects** expected in ultra-hot Jupiter atmospheres. These models will help us understand how magnetic fields may alter atmospheric circulation, thermal structure, and the vertical/horizontal transport of atomic species — potentially explaining the tentative Ti detection and Fe non-detection.

A manuscript describing these results and the new GCM framework is currently in production.

Preliminary Conclusions

- Successfully reduced GHOST spectroscopy data and have a functional analysis pipeline.
- The cross-correlation analysis is actively underway. No clear detection of Iron (Fe I) yet, but a tentative detection of Titanium (Ti) was made.
- Ongoing work includes deeper investigation of other chemical species and **GCM simulations including magnetic effects** to characterize this extreme planet.
- The associated paper is currently in production.

Acknowledgments

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