

Magnetic field strengths of hot giant exoplanets consistent with Solar System values

Julia V. Seidel^{1,2*}, Vivien Parmentier¹, Bibiana Prinoth^{3,4},
Thea Hood¹, Nishil Mehta¹, Valentin De Lia¹,
Konstantin Batygin⁵, Tristan Guillot¹, Ragnar Van den Broeck¹,
Hayley Beltz^{6,7}, Brian Thorsbro^{1,3}, Florian Debras⁸,
Daniel D. B. Koll⁹, Thaddeus D. Komacek¹⁰, Emily Rauscher¹¹,
Lorenzo Pino¹², Matteo Brogi^{13,14}, Joost P. Wardenier^{15,16},
Jacob L. Bean¹⁷, Björn Benneke^{15,18},
Jean-Michel L. B. Desert^{19,20,21}, Pablo Drake¹,
Siddharth Gandhi^{22,23}, Mark Hammond¹⁰, David Kasper¹⁷,
Michael R. Line²⁴, Elspeth K. H. Lee²⁵, Stefan Pelletier²⁶,
Andreas Seifahrt²⁷, Adrien Simonnin^{1,3}, Peter C. B. Smith²⁴,
Kevin B. Stevenson²⁸

^{1*}Laboratoire Lagrange, Observatoire de la Côte d'Azur, CNRS,
Université Côte d'Azur, Nice, France.

²European Southern Observatory, Alonso de Córdova 3107, Vitacura,
Región Metropolitana, Chile.

³Lund Observatory, Department of Physics, Lund University, Lund,
22100, Sweden.

⁴European Southern Observatory, Karl Schwarzschild Str 2, Garching
bei München, 85748, Germany.

⁵Division of Geological and Planetary Sciences, California Institute of
Technology, Pasadena, CA, 91125, USA.

⁶Department of Astronomy, University of Maryland, College Park, MD,
20742, USA.

⁷Department of Physics and Astronomy, University of Kansas,
Lawrence, KS, USA.

⁸IRAP, Université de Toulouse, CNRS UMR 5277, Toulouse, 31400,
France.

⁹School of Physics, Peking University, Beijing, 100871, People's
Republic of China.

- ¹⁰Department of Physics, University of Oxford, Oxford, OX1 3PU, UK.
- ¹¹Department of Astronomy and Astrophysics, University of Michigan,
Ann Arbor, MI, 48109, USA.
- ¹²INAF Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5,
Firenze, 50125, Italy.
- ¹³Dipartimento di Fisica, Università degli Studi di Torino, Torino, Italy.
- ¹⁴INAF Osservatorio Astrofisico di Torino, Pino Torinese, 10025, Italy.
- ¹⁵Institut Trottier de recherche sur les exoplanètes, Université de
Montréal, Montréal, Québec, Canada.
- ¹⁶Weltraumforschung und Planetologie, Physikalisches Institut,
University of Bern, Sidlerstrasse 5, Bern, 3012, Switzerland.
- ¹⁷Department of Astronomy and Astrophysics, University of Chicago,
Chicago, IL, 60637, USA.
- ¹⁸Department of Earth Planetary and Space Sciences, University of
California Los Angeles, Los Angeles, CA, 90095, USA.
- ¹⁹Leibniz Institut für Astrophysik Potsdam, An der Sternwarte 16,
Potsdam, 14482, Germany.
- ²⁰Anton Pannekoek Institute for Astronomy, University of Amsterdam,
Science Park 904, Amsterdam, 1098 XH, The Netherlands.
- ²¹DESY, Platanenallee 6, Zeuthen, 15738, Germany.
- ²²Department of Physics, University of Warwick, Coventry, CV4 7AL,
UK.
- ²³Centre for Exoplanets and Habitability, University of Warwick,
Coventry, CV4 7AL, UK.
- ²⁴School of Earth and Space Exploration, Arizona State University,
Tempe, AZ, 85281, USA.
- ²⁵Center for Space and Habitability, University of Bern,
Gesellschaftsstrasse 6, Bern, 3012, Switzerland.
- ²⁶Observatoire astronomique de l'Université de Genève, 51 chemin
Pegasi, Versoix, 1290, Switzerland.
- ²⁷International Gemini Observatory NSF NOIRLab, 950 N Cherry Ave,
Tucson, AZ, 85719, USA.
- ²⁸JHU Applied Physics Laboratory, 11100 Johns Hopkins Rd, Laurel,
MD, 20723, USA.

*Corresponding author(s). E-mail(s): jseidel@oca.eu;

Abstract

Magnetic fields are ubiquitous in the universe. In the context of exoplanets, however, their strength and prevalence remain poorly constrained, with only indirect observational limits available to date. They play a key role in shaping the activity of stars, the habitability of rocky planets, and the long-term retention of planetary atmospheres. Theoretical scaling laws are largely constrained by the limited set of stars and Solar System planets, leading to a wide range of possible values for hot giant planets outside of the Solar System, from fractions of the Jovian field to orders of magnitude larger. Ultra-hot Jupiters, with their highly ionised atmospheres, provide a new avenue to probe magnetic effects, as their atmospheric circulation could be directly sensitive to atmospheric magnetic field strength. However, it remains unclear whether magnetic effects can be observationally identified in exoplanet atmospheres and used to constrain their field strengths. Using high-spectral resolution observations targeting the planetary iron lines, we measure the Doppler shift and thus the wind speed of seven transiting ultra-hot Jupiters. We find a clear decrease of wind speed with increasing planetary temperature, a trend inconsistent with purely hydrodynamic mechanisms but naturally reproduced by magnetic drag. From this relation, we estimate the possible strength of magnetic fields of hot giant planets to at most a few gauss—comparable to the Jovian equatorial field. Our results support the idea that magnetic fields affect the atmospheric circulation of ultra-hot Jupiters and could provide a crucial benchmark for scaling laws used to predict magnetic fields in exoplanets, from hot Jupiters to rocky Earths, with additional implications for future direct observations.

1 Introduction

For gas giant planets, such as Jupiter, interactions between the atmospheric flow and the atmospheric magnetic field (for Jupiter varying between $\sim 4\text{ G}$ at the equator and a maximum of $\sim 21\text{ G}$, [1]) lead to a dissipation of the atmospheric jets at pressures where hydrogen becomes conductive [2, 3]. Such dissipation, when applied to hot exoplanets, could be strong enough to explain the long-standing issue of their inflated radii [4, 5].

Numerous theories have been proposed to provide a unified description of magnetic field formation in stars and planets via a scaling law that depends on the heat convective flux [6]. For hot Jupiters, the predictions based on this scaling law differ widely. On the one hand, models predict magnetic fields of hundreds of gauss for hot giant exoplanets [7, 8] based on the implicit assumption of additional heat deposited in the deep, dynamo region. On the other hand, recent works accounting for the feedback between induced currents in hot atmospheres and the convection-supported dynamo field [9–11] predict a low magnetic field with at most a few gauss for the same class of hot exoplanets.

Thus far, the wide diversity of magnetic fields among Solar System planets, together with the absence of direct measurements for exoplanets, limits the benchmarking of these two opposed predictions and, in consequence, our understanding of

magnetic fields in planets. Another important complication is the high ionisation of these planets, leading to the possibility of large induced fields [12].

Observationally, promising results were shown for star-planet-interactions (SPI) measurements based on activity indicators for planets in extremely short orbits [13–16] which can e.g. be observed via the modulation of the Ca II doublet lines as a function of orbital phase [17, 18] or light curve asymmetries [19–21]. However, both techniques are highly susceptible to false positives as stated in the respective works themselves, particularly those arising from stellar activity or the underlying dependence on the specific SPI modeling. While their tentative results of hundreds of gauss for the atmospheric magnetic field strength support the high magnetic field regime hypothesis, these results have to be interpreted with caution.

If the order of magnitude result from SPI works holds true, the associated radio frequencies (100 G corresponding to 280 MHz) should be observable routinely with current facilities. Surprisingly, decades of search for radio emission signals [22–25] have led to a single tentative detection by [26] that could not be confirmed through follow-up observations [27]. Possible reasons for this lack of detection are the naturally transient and directional nature of radio emissions [28] and potentially the shielding mechanisms of the highly ionised atmospheres of hot planets [29]. In fact, it is the inherent directional nature requiring beaming in the line of sight that does not allow to place a firm upper limit on magnetic fields from such non-detections as they could simply reflect an unfavourable geometry or a lower than expected radio flux. Moreover, current ground-based radio observations of exoplanetary magnetic fields are inherently restricted due to strong attenuation of high-frequency radio waves in Earth’s ionospheric D layer, most severe below 10 MHz. This translates into an observational cut-off corresponding to a minimal observable magnetic field strength of ~ 3.6 G [30]. In light of these limitations and the long-standing difficulty of securing a detection, it is worth considering—without excluding the possibility of future breakthroughs—that the absence of firm radio emission observations from hot exoplanets may reflect an intrinsic upper limit to the strength of their magnetic field.

As an alternative, the atmospheric magnetic field strength could be deduced indirectly for planets outside of the Solar System. In this context, ultra-hot Jupiters with temperatures above 2000 K provide an exceptional opportunity. Due to tidal synchronisation, the rotation period of ultra-hot Jupiters is expected to be significantly longer than the Solar System gas giants at the order of days instead of ~ 10 hours for Jupiter or Saturn. This implies a much diminished role of the Coriolis force on the winds of ultra-hot Jupiters. Secondly, the energetic input into ultra-hot Jupiter atmospheres exceeds Earth’s insolation by three orders of magnitude on average. In consequence, the stellar irradiation dwarfs the intrinsic planetary heat flux. Combining both leads to a strong day-to-night-side temperature gradient which drives sub-stellar to anti-stellar flow - from here on called day-to-night-side wind [31]. Without taking other processes into account, in a purely hydrodynamical scenario, wind speeds of this day-to-night-side wind should increase with increasing equilibrium temperature [32].

However, in ultra-hot Jupiter atmospheres, thermal ionisation of alkali metals might lead to a strong coupling between the atmosphere and their atmospheric magnetic field inducing mainly Ohmic drag [for planetary equilibrium temperatures beyond

1600 K, 4, 5, 33]. Particularly, similar to the processes in the deep layers of Jupiter, Ohmic drag is expected to slow the wind speed. Given that ionisation increases rapidly with temperature, magnetic drag would lead to decreasing wind speeds with increasing temperature [5, 34, 35].

As proposed early on by [36] and equally shown in [11] directly measuring the speed of the planetary winds for a population of exoplanets beyond the 1600 K temperature limit, such as ultra-hot Jupiters, allows us to establish if Ohmic drag is likely the main driver of kinetic energy dissipation in hot atmospheres. If this trend can be observed, it provides us with the opportunity to estimate the order of magnitude of atmospheric magnetic fields for planets outside of the Solar System by measuring the speed of the planetary winds and discriminate between the two postulated field strength regimes. Any such method, however, would be sensitive to the total atmospheric field, that is composed of the sum of the deep-seated dynamo field and the field induced by the atmospheric motions and therefore can only provide order of magnitude estimates.

Wind speed measurements on exoplanets have become routine with the arrival of ultra-stable, ultra-precise high-spectral resolution spectrographs on large telescopes such as ESPRESSO [37] and MAROON-X [38]. These instruments are capable of resolving the wind-induced Doppler shifts in the planetary spectral lines, which has allowed the community to characterize the wind profiles in exoplanets in unprecedented detail [e.g. 39–43]. [44] presents a summary of the reported day-to-night side winds and describes a heterogeneous picture without a clear overarching trend as a function of temperature [see similarly 45, for implications on Ohmic drag]. However, these conclusions are drawn from datasets reduced by different groups and are further shaped by the underlying assumption that the various atmospheric tracers used to infer these winds are equivalent in origin and diagnostic power. Yet, different tracers are potentially sensitive to different regions of the atmosphere [43, 46], taken with different instruments and wavelength ranges, as well as applied to different classes of planets that might be affected by different physics. This highlights the need for a clearly defined study sample, such as ultra-hot Jupiters in our case, analysed homogeneously with the same atmospheric tracer and the same observational setup to mitigate biases.

2 Transit spectroscopy observations

For this homogeneous population study shown in Extended Data Figure 1 and Extended Data Table 1, we select iron as our atmospheric tracer because its rich forest of spectral lines in the optical makes the observations more robust against local noise than single-line measurements. Compared to other refractory species, iron is found to be a robust tracer of planet metallicity, making our study less sensible to temporary changes [47].

We focus on Jupiter-sized targets observed with either MAROON-X on Gemini-North or ESPRESSO at ESO’s VLT on Paranal Observatory because of their high spectral resolution, wavelength coverage and most importantly telescope mirror size and resulting signal-to-noise ratio (S/N). The data was either directly acquired from

the informed principal investigators (PIs) or downloaded from the ESO archive in the case of public - and prior published - ESPRESSO data.

The overview of the data with the named targets, as well as the details of the analysis and necessary corrections such as the telluric or the Rossiter-McLaughlin effect corrections are described in the Methods (Section 5.1). Importantly, this also includes our measurement of the largest uncertainty on the velocity, the system velocity - between the barycenter of the host system and the Solar System - which can be poorly constrained in the literature (see Methods Section 5.1.5).

We cross-correlate the iron template from [48] with our data using `tayph` [49]. Given the uncertainty on the orbital velocity, we marginalise over the orbital velocity as well as over the planetary wind velocity. The resulting detection maps for each target can be found in Extended Data Figure 2.

The resulting line-of-sight atmospheric wind speeds derived from the iron lines' Doppler shift are shown in Figure 1. We find that the average day-to-night wind speeds at the terminator of ultra-hot Jupiters range from approx. 7 km/s (WASP-76 b) to less than 2 km/s (WASP-189 b). Figure 1 shows a decreasing trend of the wind speed as a function of equilibrium temperature for planets with equilibrium temperatures above 1600 K, which marks an important result emerging from the study of the population of ultra-hot Jupiters instead of singular objects.

3 Interpretation of the observed velocity trend

For tidally locked planets, wind speeds are expected to increase with temperature: higher planetary temperatures amplify the day-night contrast, strengthening the pressure gradient that drives atmospheric flow [31]. This trend, however, cannot persist indefinitely, as winds are ultimately limited by dissipative processes. Our observation that wind speeds decrease with increasing temperature indicates that the efficiency of the mechanisms dissipating atmospheric flow must rise sharply with equilibrium temperature across the range probed by our sample.

3.1 Evidence for Ohmic dissipation

Ultra-hot Jupiters are dominated, in their upper atmospheres before the effects of escape are notable, by a global sub-stellar to anti-stellar flow [39, 43, 50, 51]. The magnitude of this flow is determined by the balance between the input energy source, which is mainly the stellar irradiation, and the dissipation of energy by different mechanisms. These can either be due to hydrodynamical instabilities (e.g. Rayleigh-Taylor instabilities [52], shocks [53, 54], or, specifically for ionised atmospheres, Ohmic drag [5, 55]. In such a framework, the scaling of the dissipation mechanisms with the planetary temperature is what determines the scaling of the winds with planetary temperature at the population level.

One way to quantify this equilibrium is by considering atmospheres as heat engines. This approach has proven fruitful for the understanding of hurricanes on Earth [56] and rocky exoplanets [57], and was proposed in [58] for the application to hot and ultra-hot Jupiters.

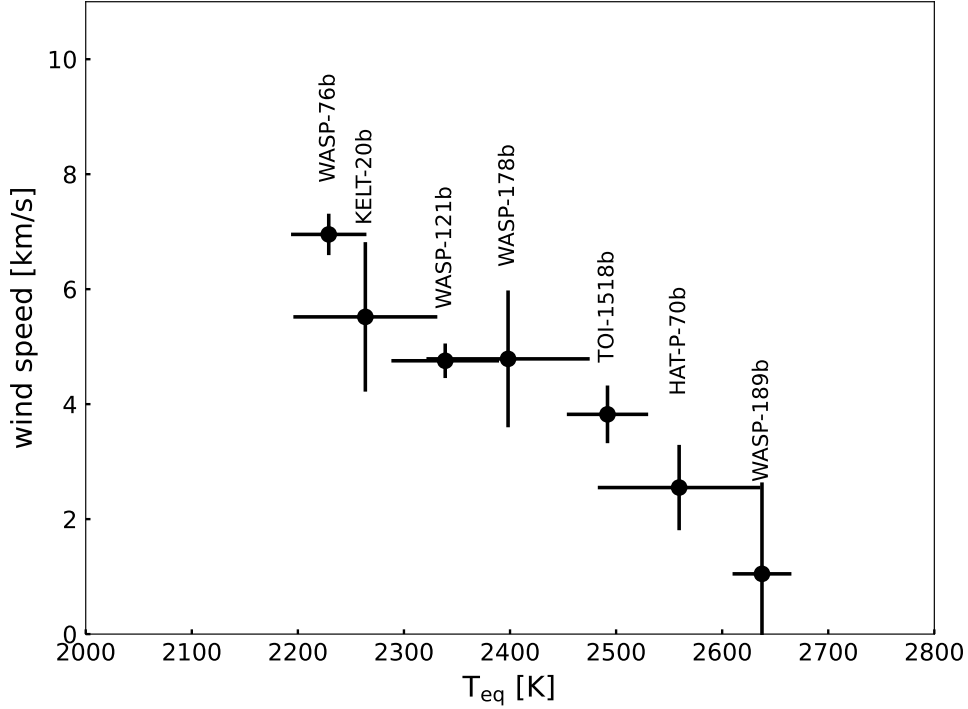


Fig. 1 A clear trend of decreasing wind speeds with equilibrium temperature. We show day-to-night line of sight wind speeds for the available population of ultra-hot Jupiters as measured from iron with a clear decrease in wind velocity as a function of equilibrium temperature. The uncertainty of the equilibrium temperature is the error propagation of the effective temperature of the star and the stellar radius to semi-major axis ratio in the calculation of the planet’s equilibrium temperature. The uncertainty on the wind speed is the fit uncertainty of the observed cross-correlation peak, taking into account the photon noise of the data, as well as the propagated uncertainty of the system velocity measurement.

This framework, described in more detail in the Methods 5.2, ultimately links the kinetic energy dissipation as a function of planetary temperature to the drag time scale (see Extended Data Figure 5) and accounts for the geometry of the atmospheric dynamics by scaling to Global Circulation Models (GCMs, see Extended Data Figure 4).

Hydrodynamical processes have been proposed to limit wind speeds in hot Jupiters, with shear instabilities and shocks identified as the most likely candidates. As shown in [58], for the case of planetary-scale hydrodynamic instabilities, the wind speed is still expected to increase with temperature as $T_{eq}^{4/3}$ (see their equation 15). Similarly, if winds were limited by shock dissipation, they would likely scale with the sound speed, as $\sqrt{T_{eq}}$. As shown in Figure 2, the observed decrease in wind speed with temperature is consistent with predictions from the magnetic drag model, while the

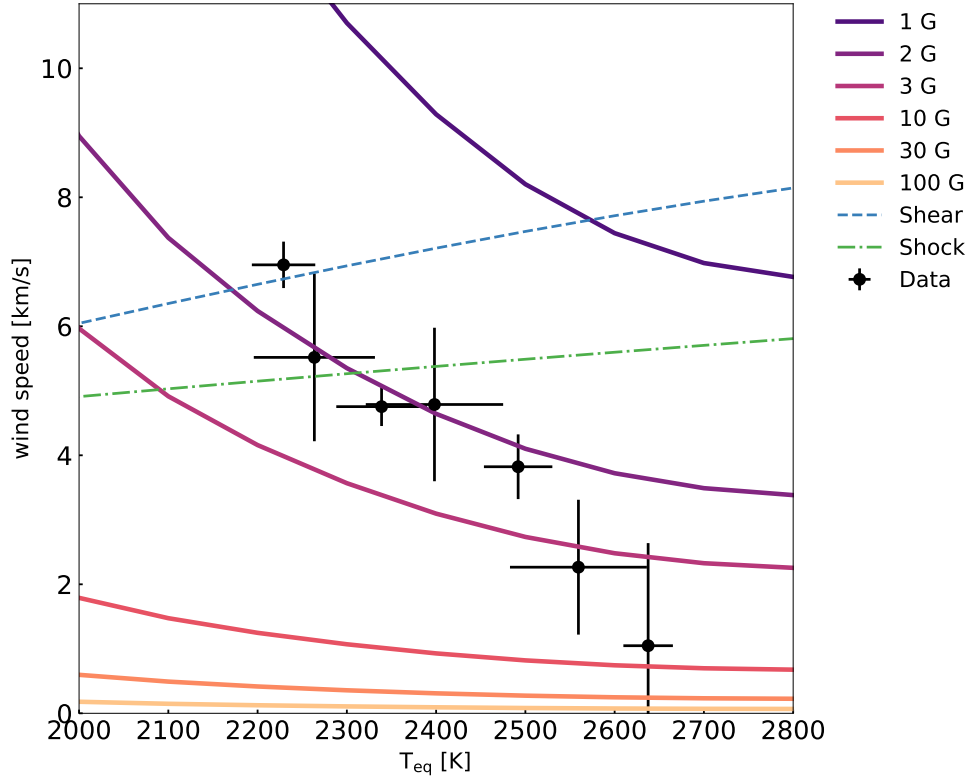


Fig. 2 Ohmic drag models reproduce the observed trend of decreasing velocities. We show the measured velocities as data points with the Ohmic drag models for ultra-hot Jupiters colour coded at different atmospheric magnetic field strengths. For comparison the classical models only invoking shear instabilities (dashed) or shocks (sound speed, dashed dotted) to dissipate kinetic energy are shown. The data points and uncertainties are taken from Figure 1.

hydrodynamic shear instability (instability scale as the planetary diameter) and shock-limited models are clearly incompatible with the data. We thus conclude that Ohmic drag is the most likely mechanism that limits the wind speed in ultra-hot Jupiter atmospheres.

3.2 Estimation of the atmospheric magnetic field strength

Whereas the slope of the wind–temperature relation provides evidence for Ohmic drag acting to slow the winds, the absolute wind speed can be used to infer the approximate atmospheric magnetic field strength.

In order to link the observed wind speed to the atmospheric magnetic field values, we need to determine which pressure levels are probed by the observations. We do this by calculating the contribution with a framework designed specifically for cross-correlation spectroscopy (see Extended Data Figure 6). We find that our observations

probe from 1 to 100 mbar with a maximum of the contribution function at 30 mbar. In order to derive our estimate of the atmospheric magnetic field, we averaged the ionisation fraction at all pressure levels using the contribution function as a weighting factor (see 5.2.2 for more details). Finally, atmospheric retrievals have shown that the refractory abundance in ultra-hot Jupiter atmospheres is similar to the metallicity of their host star [47, 59, 60]. Given that hot Jupiter host stars are slightly enriched in metals, we used a metallicity of 0.15 dex, following the peak of the population [61]. One important limitation of the applied model is the lack of induced fields which play a significant role on the day-side of ultra-hot atmospheres where the magnetic Reynolds number is large, $Re_m \gg 1$ [12, 35, 62], as well as the likely stronger impact of the radial component of the induced force on the total drag experienced by the atmosphere. While the mere fact that the day-to-night side flows are preserved and reduce in strength with temperature indicates small magnetic fields in itself, be it radially or otherwise [36], we caution against an over-interpretation of the applied model beyond the order of magnitude scale and invite self-consistent MHD follow-up work.

As shown in Figures 2 and 3, our wind speed measurement of the five planets between 2200 and 2500 K points towards a constant magnetic field of at most 2 G, with little variation between targets. For the hottest two planets we derive larger magnetic field values (up to 6 G), although with much larger errorbars.

In inverting the wind speed measurements into atmospheric magnetic field strength, we made multiple informed choices about several atmospheric parameters. As discussed in more detail in the Methods 5.2.2, the main source of uncertainties in our estimate comes from the estimate of the contribution function, the temperature that is relevant to calculate the ionisation fraction, and a possible projection factor between the actual wind speed and the measured winds projected along the line-of-sight. Whereas all these have an effect on the measured wind speed, Figure 3 shows that all caveats would bias us towards lower atmospheric field strength, meaning that we can firmly limit the atmospheric magnetic field of hot gas giants to a few gauss.

Nonetheless, our derivations provide a remarkably narrow range of potential magnetic field strengths and most importantly show that the atmospheric fields are likely homogeneous across the population of ultra-hot gas giants.

4 Discussion and Conclusion

The absolute atmospheric magnetic field strength of exoplanets has been a long standing open question, with direct observations intrinsically limited to large field strengths and indirect methods plagued by false positives. As a consequence, it was unclear up to now whether scaling laws derived from observations of stars and in-situ measurements of solar-system planets could indeed apply to exoplanets and potentially inform habitability as different applications yielded predictions ranging from several hundred to a few gauss. In this work, we observe that wind speeds in ultra-hot Jupiters decrease very strongly with planet temperature. We further show that Ohmic drag is the best explanation for this decrease, due to the strong temperature dependence

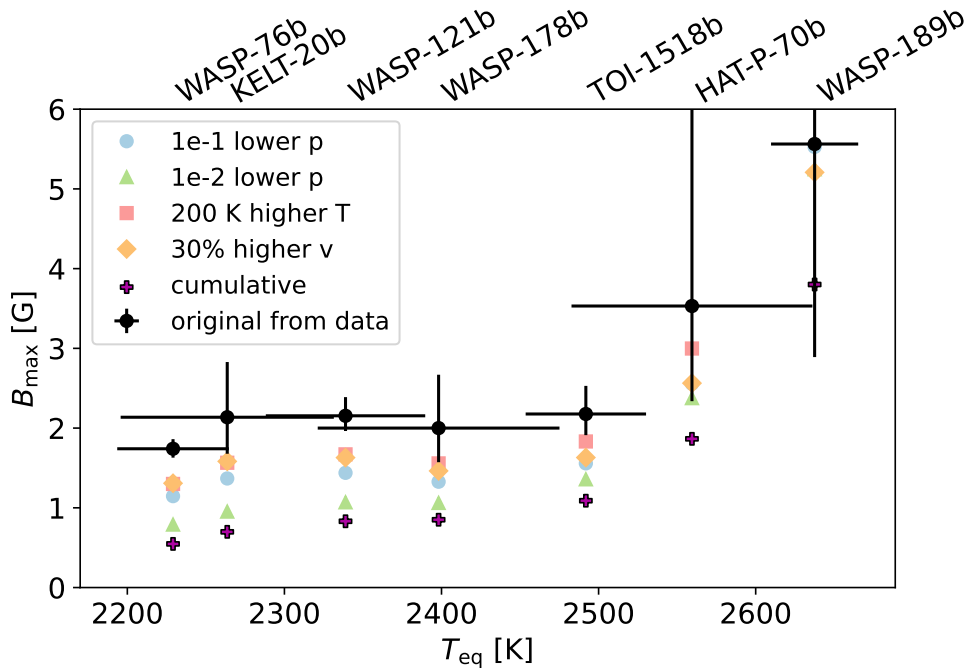


Fig. 3 Ultra-hot Jupiters have maximum atmospheric magnetic field strength compatible with Jovian values. We show the derived maximum atmospheric magnetic field strength as a function of equilibrium temperature with the values derived with uncertainties through error propagation from the data in Figure 1. Additionally, we provide the main impacts that could create deviations on the absolute atmospheric magnetic field strength, notably order of magnitude deviations in pressure, the maximum deviation from the equilibrium temperature, and an underestimation of the absolute wind speed velocity from the line of sight measurement. The cumulative impact of all these effects is marked with a dark cross. These are order-of-magnitude estimates of the average atmospheric field in the equatorial regions, including both the deep-seated dynamo field and the field induced by the atmospheric flow.

of the atmospheric conductivity. Our observations rule out the possibility of negligible magnetic fields for ultra-hot planets and demonstrate that atmospheric magnetic fields of ultra-hot Jupiters likely do not exceed field strengths of a few gauss.

4.1 From atmospheric to deep-seated dynamo magnetic fields

Our measurements are sensitive to the averaged dayside atmospheric field (especially its radial component), which, for ultra-hot Jupiters, is a combination of the deep-seated dynamo field and the induced field. Indeed, as shown in multiple MHD works, the high magnetic Reynolds number regime of these objects means that the induced field can dominate over the deep-seated dynamo field, and can even self-sustain without a deep field [12, 35, 62]. However, our observations can shed light on the order of magnitude of the deep-seated dynamo field. Indeed, if the deep-seated dynamo field were of the order of hundreds of gauss, as proposed by [7, 8], the induced field would have to be

fine-tuned to have the opposite sign and very similar magnitude of the background field, in order to have a combined smaller field of a few gauss for *all* planets in the studied population. As this scenario is exceedingly unlikely, we propose that the deep-seated dynamo field of ultra-hot Jupiters cannot be larger than a few gauss. Our estimate is in line with the recent theoretical estimates by [10], which show that the Ohmic dissipation can shut down the convective motions in the outer convective zone, reducing the strength of the dynamo field ”to or below Jupiter’s”.

4.2 Consequences for future observational programmes

Decades of large programmes to directly observe the magnetic field strength of exoplanets have thus far only yielded tentative upper limits for potential magnetic fields [26, 27], with the strong caveat that these upper limits assume emission in the line of sight of the observer.

Similarly, modeling the polarimetry signature of helium as proposed in [63] results in estimates of the order of 0.1 G [64, 65] to explain the observed atmospheric escape. Considering the difference in altitude between our atmospheric magnetic field strength measurements and their estimates related to the outflow of the exosphere, the weaker field might be a simple result of the attenuation of magnetic fields by the cubed radius distance relation and is likely compatible with our results. More recently, [66] suggested that the velocity difference between neutral and ionised species could be used to estimate exoplanetary magnetic fields. However, even a relatively strong field of 10 G - three times the equatorial field of Jupiter - would produce an average velocity difference of only $\sim 1 \text{ kms}^{-1}$, implying a detection threshold comparable to that of direct radio observations.

We show, from a homogeneous study of ultra-hot Jupiters, that wind speed decreases strongly with planetary temperature, which provides observational evidence for the presence of Ohmic drag. Our measurements are compatible with a near-Jovian atmospheric magnetic field strength for these planets, ruling out the presence of magnetic fields of tens or hundreds of gauss. This is in agreement with recent theoretical studies predicting Jovian-like magnetic fields based on an improved interpretation of the scaling laws applicability to strongly irradiated planets. Our work has strong implications for the observations of exoplanetary coherent radio emission, although generated largely by the radial component of the Lorentz force to which we are less sensitive. Nonetheless as previously discussed an order of magnitude difference between the different directional components can be ruled out by the simply existence of day-to-night flows [36]. Since the electron cyclotron frequency is $\nu = 2.8B \text{ [G] MHz}$, potential signals from ultra-hot Jupiters would lie very close to the $\sim 10 \text{ MHz}$ ionospheric cutoff, hampering detectability (e.g., [23, 24]). Among other factors, our order of magnitude estimate might, therefore, naturally explain the current lack of confirmed radio observations despite decades-long campaigns.

5 Methods

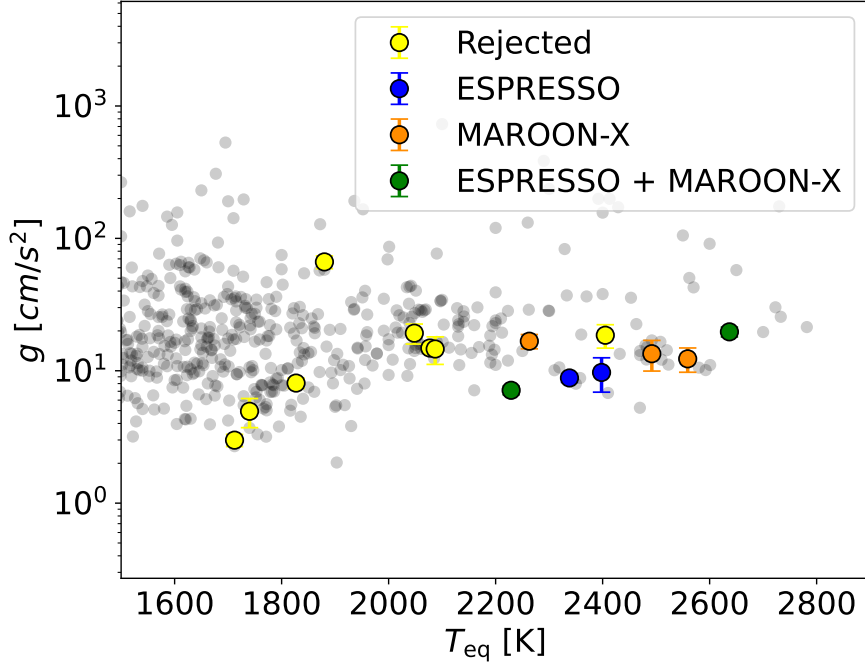
5.1 Data preparation

In Extended Data Figure 1 we show all considered targets as a function of their equilibrium temperature which we have re-calculated for homogeneity assuming zero albedo instead of relying on reported values that include dayside measurements. The overview of the data can be found in Extended Data Table 1. All masses stem from the respective discovery papers and their RV analysis, except KELT-20 b and HAT-P-70 b which stem from the transit observation scaling in [47]. We found no trend in planetary mass and radius, highlighted by the similar value for the gravity in our sample (see Extended Data Figure 1). Nonetheless, we report the values for the planets with an iron signature in Supplementary Table 1. The rejected targets (mostly due to a lack of iron signature) show that the window of observable iron signatures lies in the equilibrium temperature window identified by [58] where the dissipation of kinetic energy in the atmosphere is likely dominated by Ohmic dissipation ($T_{\text{eq}} > 1400 \text{ K}$). We specify in the following which targets were deemed suitable for the survey and the individual rejection reasons per targets and dataset.

5.1.1 Rejected planets from the survey

KELT-4 b, KELT-7 b, and MASCARA-4 b are orbiting pulsating host stars [72, 76, 77]. The proper extraction of atmospheric signatures for systems around pulsating host stars is an ongoing investigation within the field and not suitable as of yet for a robust population study. Three other planets in our sample did not show a detectable iron signature. WASP-173 b is an extremely heavy target leading to a severely reduced signal which can explain the non-detection, while KELT-11 b and WASP-172 b did not show a significant enough iron feature to be included in the survey. KELT-17 is a chemically peculiar Am star, making the recovery of any planetary signal extremely challenging and - if achieved - prone to extreme stellar contamination [78]. We excluded the observations of WASP-19 b entirely due to low S/N across all four nights and encourage additional observations of this object. Similarly, we discarded the night of 18 Oct 2019 for WASP-76 b for the same reason. For WASP-121 b, we only used the data taken in 4-UT mode, as its superior photon-collecting power dominates the observed signal (see S/N for WASP-121 b in Extended Data Table 1). The constraint of the resolved iron detections naturally downsizes to a sample to ultra-hot Jupiters only, where iron is present in the atmosphere in atomic form [79, 80].

Two planets which are not included in our survey but technically classified as ultra-hot Jupiters are WASP-33 b and KELT-9 b. For WASP-33 b, PEPSI data exist which report a wind speed measurement [81], however, WASP-33 is a pulsating host star as evidenced by the clear pulsation pattern of the host star in [82]. In the mentioned paper the impact of the pulsating host star is reflected in the excessively large uncertainty, making WASP-33 b unsuitable for a robust population survey. KELT-9 b, as a northern target, unfortunately only has transit observations available with HARPS-N [83] as the large majority of KELT-9 b observations are in emission, unsuitable for our survey. Additionally, with an equilibrium temperature of more than 1000 K above even the hottest ultra-hot Jupiter in our survey [84], KELT-9 b represents a class of its own



Extended Data Figure 1 Exoplanet population overview with the studied targets highlighted in the temperature vs gravity space. All selected targets are Jupiter-like targets with resolved iron detections from 8m-class telescopes. The background targets in transparent black are all available entries from the NASA exoplanet archive with constrained masses and radii (accessed 27-May-2025). The errorbars represent the propagated uncertainties of measured mass and radius.

and should be treated as such. Higher order effects mentioned in the main paper likely impact KELT-9 b which make any wind speeds measured for this planet non representative of the derived trend.

5.1.2 Data cleaning steps

The ESPRESSO observations were reduced using the dedicated ESPRESSO pipeline (ESPR v3.2.0) via `esoreflex` (v2.11.5), provided by ESO and the ESPRESSO consortium. For our analysis, we used the non-blaze-corrected, two-dimensional order-by-order spectra from fibre A (S2D) for cross-correlation, and the one-dimensional flux-calibrated spectra from fibre A (S1D) for telluric correction.

The MAROON-X observations were reduced using the standard pipeline described in [38], which extracts wavelength-calibrated, two-dimensional spectra order-by-order from each exposure in the time series, separately for the blue and red arms. Due to differences in exposure times, we treated the two arms independently. As the pipeline does not output stitched one-dimensional spectra (analogous to ESPRESSO’s S1D), we manually combined the orders to create a single spectrum for telluric correction.

We corrected for telluric contamination in all datasets using the standalone version of `molecfit` (v1.5.9; (author?) 85, 86). We fitted the telluric model to each exposure individually, using spectral regions with strong telluric H₂O and O₂ absorption near the sodium doublet at 590, and around 630, and 650 nm. The resulting models were interpolated onto the corresponding wavelength grids and divided out.

For targets observed with both spectrographs, as is the case for WASP-76 b and WASP-189 b, we also account for differences in template wavelength coverage during stacking, following the method described in [87]. For example, the MAROON-X red arm contributes less due to fewer iron lines present in this wavelength region. We check for a potential impact from the use of two different spectrographs with WASP-76 b which was observed on multiple occasions with both the ESPRESSO and MAROON-X spectrograph. We find no impact from the choice of spectrograph.

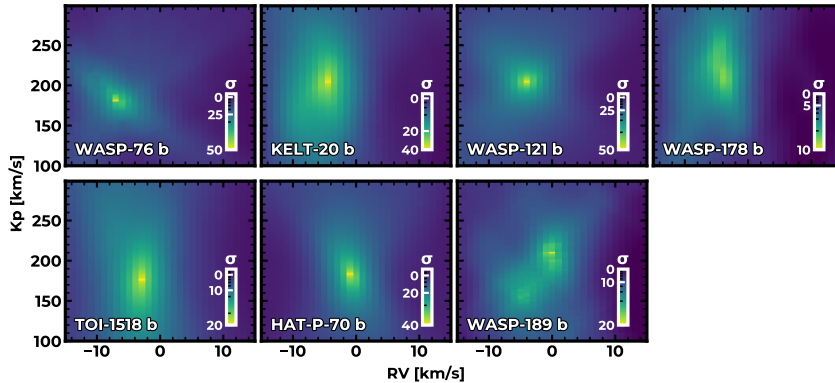
5.1.3 Cross-correlation

We searched for atomic absorption by neutral iron using the cross-correlation technique [88] as implemented in `tayph` [see e.g. 49, 87, 89, 90].

After pipeline reduction and telluric correction, we shifted the spectra to the stellar rest frame, correcting for the barycentric velocity and the stellar reflex motion due to the orbiting planet. The barycentric correction is only needed for MAROON-X observations, as the ESPRESSO pipeline provides barycentre-velocity-corrected spectra. Following [49], we removed outliers via an order-by-order sigma-clipping algorithm, using a running median absolute deviation over 40-pixel sections of the time series and rejecting 5σ outliers. Additionally, we manually masked residual telluric contamination where the flux dropped by 50% or more, primarily in the saturated O₂ band where `molecfit` corrections are inadequate. This affected on average 8.5% of the pixels for each of the observations, and at most 17.5%. We rejected individual exposures on each night if they showed significant deviations in S/N compared to the rest, or if the S/N was generally too low (approx $S/N \leq 20$) – i.e., entering the red noise regime instead of being limited by photon-noise.

Before cross-correlation, we corrected for the spectrograph response via a colour correction: we divided each order by the mean out-of-transit spectrum to assess wavelength-dependent differences, fit the residual with a third-order polynomial, and divided this fit from the original order. Note that we do not divide out the mean out-of-transit spectrum at this stage, but rather cross-correlate first and then divide the mean out-of-transit cross-correlation function. In the limit of independent stellar and planetary spectra, the order of these operations is interchangeable.

We then cross-correlated the corrected 2D spectra with a neutral iron template from [48] at 3000 K, appropriate for the range of limb temperatures in our sample. The templates assume an isothermal atmosphere in hydrostatic and chemical equilibrium and were broadened to the approximate line-spread functions of the instruments: 2.14 and 3.53 km/s for ESPRESSO (1UT-mode HR) and MAROON-X, respectively. For WASP-121 b, some of the observations were taken in ESPRESSO 4UT MR mode (see Extended Data Table 1), and the templates were instead broadened to 4.28 km/s. For the planets of the survey where iron was found we provide the K_p - V_{sys} diagrams in Extended Data Figure 2.



Extended Data Figure 2 Kp–vsys diagrams showing detected Fe I absorption in the sample. Each panel displays the stacked Kp–vsys diagram after correcting individual observations for their system velocities. The colour bars indicates 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.

5.1.4 Rossiter-McLaughlin fit

We corrected for the Rossiter-McLaughlin effect (Doppler shadow) using `StarRotator` [see 74].

In summary, we assumed that the stellar line is well-approximated by a Gaussian profile, implying that the stellar cross-correlation function also adopts a Gaussian shape. We used a grid size of 25 pixels in `StarRotator`, resulting in a total of 50×50 grid cells. For each cell, we computed a Gaussian cross-correlation function as

$$\text{CCF}_i(v) = 1 - A \exp\left(-\frac{(v_i + v_{\text{sys}} - v)^2}{2\sigma^2}\right), \quad (1)$$

where v_i is the velocity of cell i due to stellar rotation (assuming no differential rotation in the vertical direction; see (author?) 74, 92), A is the Gaussian amplitude (ranging from 0 for no absorption to 1 for saturation), and σ is the Gaussian width, determined by the instrumental profile. We accounted for limb darkening using a quadratic law, adopting coefficients from the large survey in [93]. If unavailable, we adopted limb-darkening coefficients from [76, 94, 95].

5.1.5 Measuring the system velocity

The apparent system velocity (the movement of the barycenter of the observed system with respect to the Solar System barycenter) varies slightly between spectrographs due to the lack of absolute wavelength calibration. This results in a constant offset in the wavelength solution, which we correct by independently measuring the system velocity for each observation using the out-of-transit cross-correlation functions. This also accounts for velocity offsets introduced by, for example, instrument interventions as seen e.g. for ESPRESSO in [39].

We determined the system velocity for each dataset by fitting a rotationally broadened Voigt profile [96] to the average out-of-transit cross-correlation functions, obtained by cross-correlating the processed spectra with a suitable PHOENIX model of the host star [97]. We have opted for the more complex profile in comparison to a Gaussian due to the better results for fast rotating stars with blended stellar lines ($v \sin i > 80 \text{ km/s}$). Prior to cross-correlation, the spectra were corrected for the stellar reflex motion induced by the orbiting planet and for the barycentric velocity (if not already handled by the reduction pipeline) and cleaned, see section 5.1.3. The fits were performed using `pymultinest` [98]. The results, as well as literature values for reference, are shown in Supplementary Table 2. The uncertainty of our results in the table are solely the fitting error and do not take into account that the system velocity cannot be estimated better than the $\sim 100 \text{ m/s}$ level due to the photosphere of the star itself.

Overall, we find good agreement between values measured with the same instrument even over year-long timescales. Nonetheless, when velocity precision is key, measuring the velocity in each night is necessary, see e.g. the 0.2 km/s difference for the two ESPRESSO nights of WASP-76 b. More importantly, different instruments will likely show different systemic velocities as they also include instrumental effects such as drifts and shifts in the "zero" radial velocity due to instrument interventions. As a consequence, measuring the systemic velocity becomes crucial when combining spectra from different spectrographs. Overall, the literature values and our derived values between instruments and nights are within 1σ with notable exceptions: For TOI-1518 b, we highlight that the reference value from [51] is the value as derived from SOPHIE measurements in their Appendix A, in their Table 2 a higher value is given, likely copied from [99] and a typo in the manuscript. TOI-1518, KELT-20, HAT-P-70, WASP-189 all fall, to varying degrees of severity, in the category of fast-rotating host stars which can lead to larger uncertainties. All uncertainties were derived from the 1σ envelope of the posterior distribution of the Bayesian retrieval. Most notably, the only literature value we were able to find for HAT-P-70 b from [100] with the TRES spectrograph at a 1m-class telescope is in disagreement with our observed value. Given the overall agreement of our derived values with the order of magnitude of literature values, we assume that this offset is due to the TRES spectrograph or a difference in methodology. In [100] they opted for fitting stellar line profiles derived from a least-squares deconvolution to the data which usually gives acceptable values for the RVs of fast-rotating stars. Given the goal of this study, to derive trends from the population of planets, this difference should have no impact on our results, since we correct our dataset for the measured velocity and additionally use the same method for all datasets. This means we would at most introduce an overall bias on the absolute velocity value but not change the population trend. Given the excellent agreement between literature values and our measurements, we can likely rule out such a potential bias. Nonetheless, to assure that the observed trend does not hinge on an over-confidence in the system velocity measurement we do not use the fit uncertainty to propagate uncertainties to our final velocity measurement, but instead use the variance between the literature values and our observed values as the maximum possible uncertainty (excluding the TrES spectrograph due to the mentioned discrepancies).

5.1.6 Measured offset in velocity

The offset relative to the measured system velocity, which encodes the atmospheric movement, is determined from the stacked K_p - V_{sys} diagrams. To generate these diagrams, we scan over a range of possible projected orbital velocities $K_p = v_{\text{orb}} \sin i$, avoiding assumptions about the true orbital velocity or inclination and preventing bias from their uncertainties. Additionally, the map is corrected for the system velocity as derived for each individual night prior to stacking in K_p - V_{sys} space based on S/N per night of observation. This ensures that differences in the system velocity per spectrograph or even per night due to interventions have been accounted for.

Given the rapidly growing number of line-of-sight Doppler shift velocity measurements reported in recent years, it is crucial to keep two key considerations in mind when placing our results in context with the existing literature. First, absolute velocity values are highly sensitive to the details of data post-processing and analysis—most notably to the choice of spectral template and to how the systemic velocity is derived from the data (see Methods 5.1.5 and the discussion in [101] on differences between their work and the literature on KELT-20 b, caused by the same issue). Second, planetary atmospheres are three-dimensional. The vertical stratification of their flow patterns inherently limits the comparability of wind speeds and directions when different species trace distinct atmospheric layers. Consequently, inter-species comparisons—for example, between Doppler shifts measured for iron, sodium, or helium—should be interpreted with caution, as these species probe markedly different regions of the atmosphere (see e.g. Figure 1 in [43]). This three-dimensionality is equally important in the data selection, as partial transits favour viewing geometries of one hemisphere over the other, arriving at distorted mean velocity values due to the non-symmetric impact of planetary rotation. One such example is the partial transit analysed in [102] for TOI-1518 b where seemingly their result is in tension with the velocities derived in [51] and our work if the viewing geometry of the partial transit is not accounted for. Overall, the strength of our study is the combination of a careful selection of high-quality datasets and the homogeneous data reduction and interpretation process, leading to Doppler-shift values that are comparable between planets.

5.2 Ohmic dissipation model

By applying the formalism from (author?) [58], we assume the atmosphere is a heat engine with work output rate $W = \eta Q$, where η is the engine’s thermodynamic efficiency and $Q = \sigma T_{\text{eq}}^4$ is the heating rate. With T_{eq} as the equilibrium temperature of the planet and σ as the Stefan-Boltzmann constant, it is simply the absorbed stellar flux. We further assume that, in equilibrium, all work goes into dissipating the atmosphere’s large-scale kinetic energy. This leads us to the following relation for the wind velocity in the modelled atmosphere (equation 11 in [58] where further details on the derivation can be found):

$$\text{vel} = k_0 \left(\tau_{\text{drag}} \eta \sigma T_{\text{eq}}^4 \frac{g}{p} \right)^{1/2} \quad (2)$$

where T_{eq} is the equilibrium temperature of the planet, g is gravity, and p is pressure. k_0 is a scale factor, set to 0.25 based on comparison with a recent grid of global circulation models (see Methods 5.2). τ_{drag} is the drag timescale that depends on the exact physical mechanism dissipating the energy and finally, η is the efficiency of the atmospheric heat engine. For an ideal heat engine, we can place an upper bound on η . For example, if parcels of air are heated and cooled at constant pressure, and the day-to-night temperature contrast is large, the resulting thermodynamic cycle is called an Ericsson cycle, with efficiency:

$$\eta = \frac{2R/c_p}{1 + 2R/c_p} \approx 0.36 \quad (3)$$

where R is the gas constant and c_p is the heat capacity. In practice, η is less than the value for an ideal heat engine. This is because atmospheres are not perfectly efficient. However, any difference between the real value of η and our calculation would reflect as a constant value across the population and is absorbed into k_0 . As shown in Methods Section 5.2, the heat engine model is an excellent match to complex, non-grey, global circulation models. Deviations between the wind speeds predicted by the heat engine formalism and the GCM outputs are of the order of ≈ 0.2 km/s at most. Although this points towards a variation of heat engine efficiency with temperature, it is orders of magnitude too small to explain the change in velocity that we observe in our sample.

The drag timescale used in equation 2 encompasses all the dissipation physics. It can be seen roughly as the time for a parcel of gas to lose all its velocity if all other forces were suddenly removed. Large timescales therefore mean weak dissipation, whereas small timescales mean strong dissipation. The timescales necessary to explain the measured wind speed decrease by more than one order of magnitude with temperature across our sample, going from ≈ 7 h at 2200 K to less than 15 min for our hottest target (see Extended Data Figure 5).

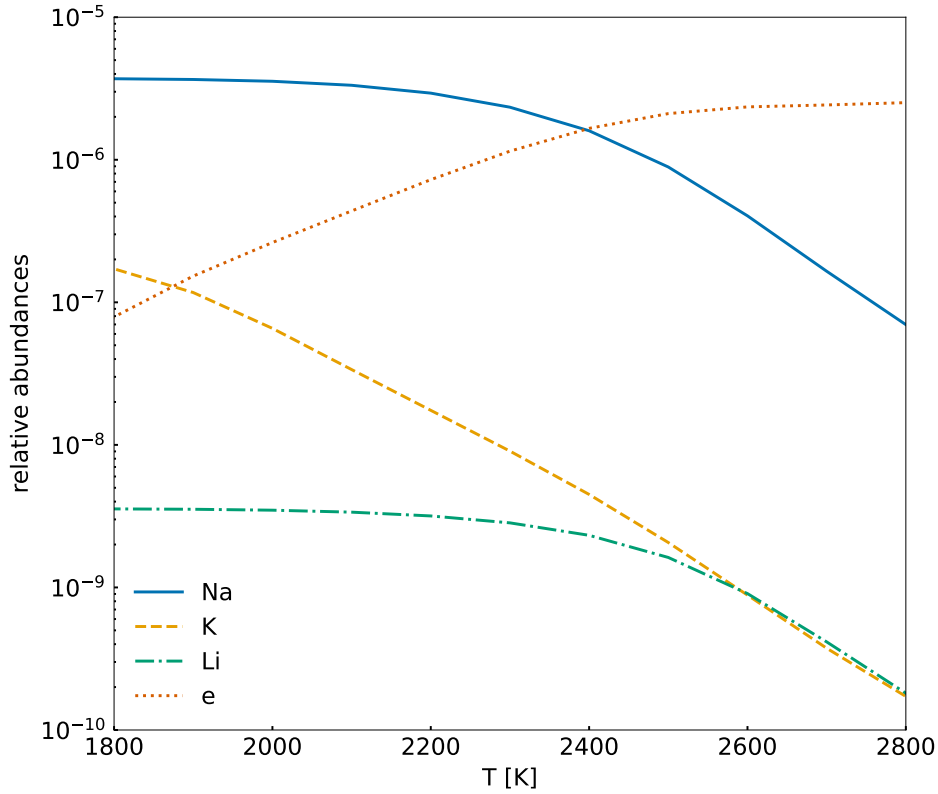
Among all the possible mechanisms that can dissipate the winds on hot exoplanets, Ohmic dissipation is the only known one that is expected to have such a strong scaling with temperature due to the strong dependence of electron density with temperature in the Saha equation. In such a case, the drag timescale can be calculated following [5, 103, 104] and taking into account [105]:

$$\tau_{\text{drag}} = \frac{4\pi H_e \rho}{B^2} \quad (4)$$

where B is the atmospheric magnetic field strength, H_e is the atmospheric magnetic diffusivity, and ρ is the gas density (inversely proportional to temperature at a given pressure level). The magnetic diffusivity is described as

$$H_e = 230\sqrt{T_{\text{eq}}}/x_e[\text{cm}^2/\text{s}] \quad (5)$$

in Equation 2 from [106], following [107], with x_e as the unitless ionisation fraction for which we use chemical equilibrium tables from [108] with the underlying chemical network from [109]. As shown in Extended Data Figure 3, the electron density increases

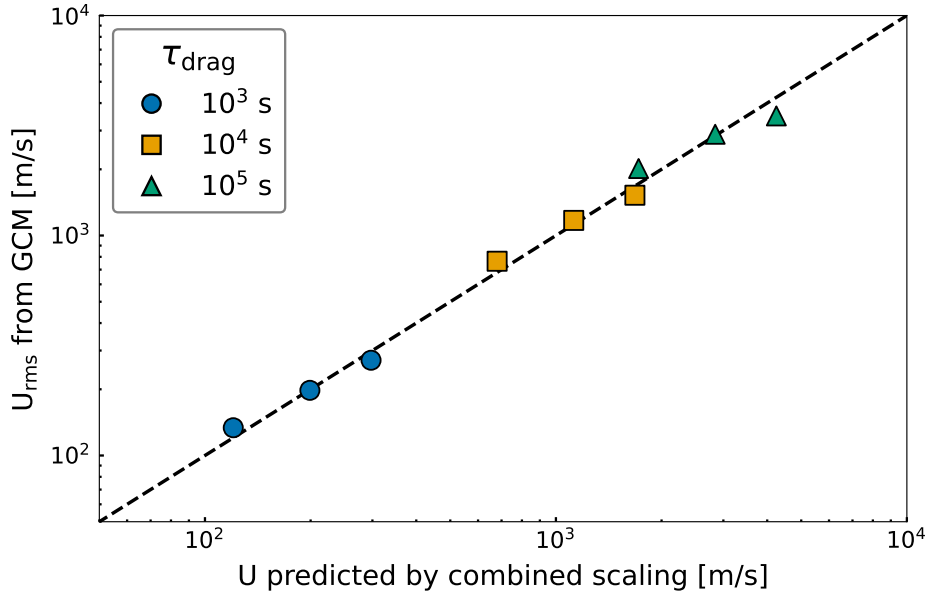


Extended Data Figure 3 Order of magnitude change in relative electron abundance over the selected temperature range. The relative abundance of the alkali metals as a function of temperature at the mbar pressure level provided by [108] is overplotted with the relative electron abundance (dashed). The underlying atmospheric chemistry is described in [109].

by an order of magnitude between 2200 and 2500 K. This hinges on the use of the correct temperature, for which we use the equilibrium temperature.

5.2.1 Model assumptions

[58] relies on various assumptions to create their models of which the most important is their treatment of hot Jupiters, compared to the ultra-hot Jupiters in our study. While they state that their work also holds for hotter planets, we will highlight some differences. Most importantly, the application of the Saha equation in [58] relies on the assumption that the main contribution to the electron abundance in the atmosphere stems from potassium. However, at the mbar pressure level and for temperatures above ~ 2000 K, potassium is fully ionised and the contribution of the partial ionisation of sodium becomes dominant, as well as the first and second valence electron removal from Fe. At these pressure levels, the electric conductivity can, as a consequence, reach



Extended Data Figure 4 Recreation of the calculation of k_0 , in line with Figure 4, panel b from [58]. The y-axis corresponds to the line of sight velocity at the terminator at the mbar pressure level in the GCM, in line with what is probed observationally. The x-axis is the calculated velocity from Equation 2 with the applied scaling. The black, dashed line indicates 1:1 equality between the GCM simulation and the scaled model. The colours highlight the applied τ time scales for different temperatures, namely 1400, 1800, and 2200 K.

values up to $\sim 1Sm^{-1}$ [103, 110, 111]. We have opted to update the literature approach to assume potassium as the main source of free electrons with the simplified Saha equation from [112] as applied in e.g. [5, 58]. Instead, we employ the pre-calculated relative abundance tables from the full Saha equation calculation as provided by [108] for an atmosphere containing all alkali metals, as well as C₂H₂, C₂H₄, C₂H₆, CH₄, CO, CO₂, CrH, Fe, FeH, H₂, H₃⁺, H₂O, H₂S, HCN, LiCl, LiF, LiH, MgH, N₂, NH₃, OCS, PH₃, SiO, TiO, and VO. Their pre-computed grid provides steps of half orders of magnitude in pressure and 100 K in temperature, sufficient for our purposes. The top panel of Extended Data Figure 3 shows the overall relative abundance of the alkalis and electrons as a function of temperature at the mbar pressure level, the bottom panel highlights the Na dominant contribution compared to K for ultra-hot Jupiters above 2000 K.

While the application of the Saha equation fundamentally impacts the form of the model via the ionisation fraction as a function of temperature, the scaling factor k_0 in Equation 2 governs the vertical anchoring of the models and thus the absolute magnetic field value since $U \sim k_0/B$. k_0 is an important scale factor, as it encodes various model assumptions, most importantly the application of an isothermal temperature profile in the atmosphere, as well as any simplifications regarding the efficiency of

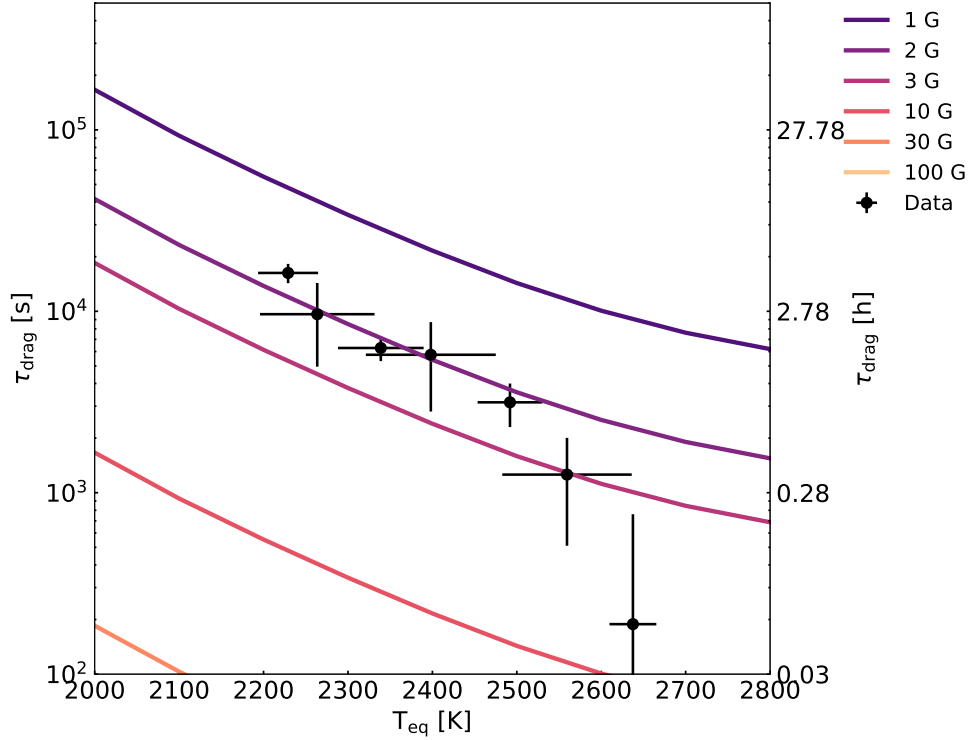
the heat engine. k_0 was set in [58] by scaling the values derived from Equation 2 for different values of τ to the output of GCM simulations, see e.g. [113]. Simply put, they anchor the calculation of the velocity of the atmosphere from the heat engine theory to GCM outputs calculated from first principle *before* introducing magnetic drag as the governing force of the drag timescale. This allows to reset the assumptions going into the heat engine calculation and give absolute values of the magnetic field strength tied to the level of realism of the applied GCM. In consequence, the choice of GCM for the applied scaling is crucial. [58] opted for the MITgcm [114] which solves the atmospheric fluid dynamics equations with a double-gray radiative transfer approach as applied in [113]. Given the rapid evolution of the field and additional assumptions on the heat engine efficiency from the treatment of ultra-hot Jupiters vs hot Jupiters in [58], we have decided to re-calculate k_0 by scaling to the non-grey SPARC/MITgcm GCM [115] as applied in [116], where the MITgcm is coupled to the plane-parallel radiative transfer code of [117]. [116] provides their pre-calculated grid of GCMs for a variety of temperatures and time scales, which we have used here for convenience. Most importantly, their GCMs include TiO/VO chemistry, although they show that including this important chemical aspect of ultra-hot atmospheres has a negligible impact on the equatorial, zonal wind speeds. The resulting scaling factor is $k_0 = 0.25$, of the same order of magnitude as the scaling factor in [58], highlighting the negligible impact of our additional assumptions. For future applications by the modelling community, we provide here the corresponding magnetic drag timescale from the observed wind speeds in Extended Data Figure 5.

Equally, [116] discusses the impact of any change in surface gravity on the equatorial zonal wind speed and finds no meaningful difference (see Extended Data Figure 1 for an overview of our targets in equilibrium temperature vs gravity space). However, they identify a dependence of the equatorial zonal wind speed on the rotation period of the planet. We found no correlation between the measured wind speed and the planetary periods. This is likely due to the short range of periods our data covers, making them an excellent sample to study effects without the additional dependency on the period. Equally, we found no trend with planet mass or radius.

5.2.2 Uncertainty estimate on the absolute atmospheric magnetic field strength

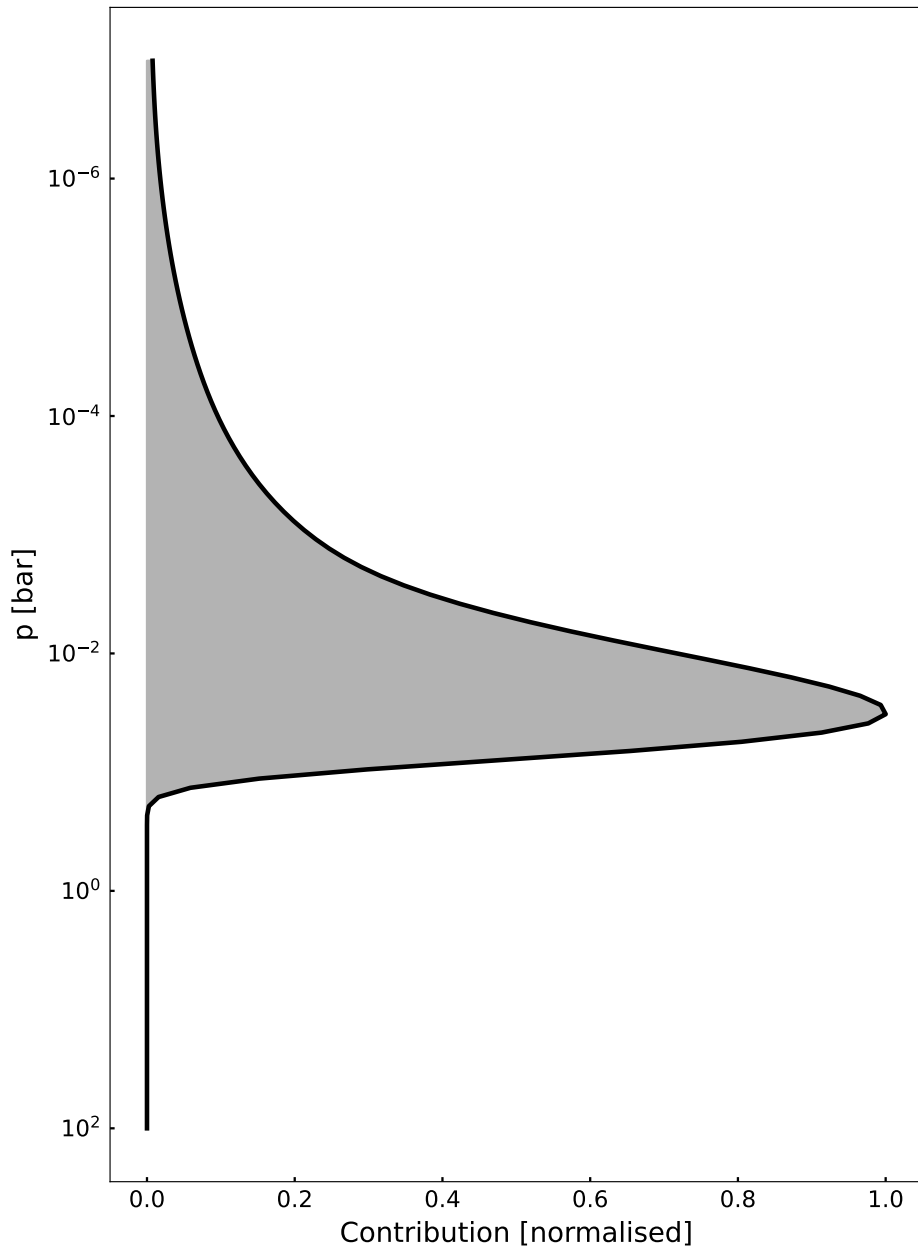
[58] assesses the impact of the temperature-pressure profile on the absolute value of their models and finds a relatively small effect which they attribute to the inverse effect of pressure and temperature on the magnetic drag timescale. However, the pressure scale has a profound impact on the absolute value of the Ohmic dissipation models due to the pressure dependency of the ionisation in the magnetic diffusivity H_e . The dependency of the velocity in Equation 2 on $1/p$ pressure is offset by the linear dependency of the density on pressure in the ideal gas law.

In order to estimate the range of pressures that are probed by the observations, we developed a new technique to determine the contribution function of the cross-correlation function. Using the radiative transfer code `petitRadTrans` [118], we calculate a first reference spectra, and then spectra where the opacity in each atmospheric layer is set to zero. Both spectra are then cross-correlated with the same



Extended Data Figure 5 Calculated values of the drag timescale with models assuming Ohmic drag. The uncertainty is the propagated uncertainty of the measured velocity in Figure 2.

template used to cross-correlate the observations. The contribution function is the normalised ratio of the maxima of the two cross-correlation functions. The resulting contribution function, shown in Extended Data Figure 6 shows that our observations probe from 1 to 100 mbar with a maximum at 30 mbar. In order to obtain the mean ionisation necessary to estimate the magnetic field, we weigh the precomputed ionisation fractions from [108] discussed in the previous section by the normalised contribution of each pressure layer, accounting for all pressure levels that contribute more than 10%. The current approach to contribution functions for cross-correlation is unfortunately flawed, as a simple setting of the opacity to zero creates a non-physical continuum contribution from aliasing. Likely, the true probing regions of the lines sit higher in the atmosphere [see e.g. 41, under the caveat that the line wings are not accounted for here, meaning this is an upper limit]. Given that we do not see iron depletion in our observations for any of the targets, we cannot be higher than at most two orders of magnitude in pressure, which is when iron ionisation becomes dominant. In order to provide the most conservative estimates, we re-calculated the magnetic field assuming that the contribution functions is inaccurate by one or two orders of magnitude in pressure. The impact of this difference can be seen in Figure 3, where a two order of magnitude difference in pressure would bias us to lower magnetic fields by roughly 1 G.



Extended Data Figure 6 The normalised contribution function. It was derived from `petitRadTrans` used for weighting of the different pressure layers with contributions above 10%.

While this gives us an accurate profile of the ionisation fraction of the probed atmosphere in the line of sight, it hinges on the metallicity, as an order of magnitude difference in metallicity has the same impact as an order of magnitude shift in pressure. [47] has shown that ultra-hot Jupiters have stellar metallicity, most importantly for iron, our atmospheric probe. The stellar metallicity of ultra-hot Jupiter host stars is known and diverges from the overall exoplanet host star population, peaking at 0.100 ± 0.012 dex (or roughly 1.25x solar) [61]. Any deviation below the order-of-magnitude level has a negligible impact on the derived magnetic field strength.

More important than the metallicity is the applied temperature as the magnetic diffusivity directly depends on \sqrt{T} as well as indirectly via the ionisation fraction. The work performed by the drag force in the heat engine model is proportional to the integral over $1/\tau$ from the sub- to anti-stellar point (from the day to the night side). While we assume τ to be constant with temperature, it is unclear to which temperature the averaged τ corresponds to and if the limb, and the equilibrium temperature, is a good approximation of the work performed to create the drag. To better constrain which temperature is an accurate reflection of reality, we have parametrised the temperature profile of WASP-121 b from sub- to anti-stellar point following the GCM models from [119], which to first order follows a sinusoidal in longitude. Calculating τ as a function of longitude and comparing the normalised integrated value of τ shows that the main contribution to the work performed by the drag force is at approximately 75 degrees, slightly offset from the limb at 90 degrees. For WASP-121 b this offset leads to an underestimation of the temperature by at most 200 K. This offset is the maximum systematic bias across the dataset and would lead to higher ionisation levels with subsequently lower magnetic field strengths (see Figure 3).

Lastly, in transmission spectroscopy when observing iron, we are sensitive to the line of sight velocity component of the day-to-night side wind, which, due to the nature of the horizontal wind direction, is largely aligned with the absolute wind speed but will always be an under-estimation. We assessed the difference between the observed velocity compared to the absolute velocity from the GCM models published in [116] and find that for drag timescales below 10^5 s the difference between the line of sight velocity and the real wind speed is at most 30% (see the impact on the atmospheric magnetic field strength in Figure 3). All of the mentioned effects that could impact our estimation of the strength of the atmospheric magnetic field would reduce its real strength and we have provided the impact of all cumulated effects with the dark crosses under each calculated atmospheric magnetic field strength in Figure 3. We find that, conservatively opting for the maximum offset from our assumptions, the maximal atmospheric magnetic field strength will be at most reduced to the order of magnitude of half a gauss and thus remains comparable to the Jovian field and overall Solar System planets.

Declarations

- Data availability: The MAROON-X data is publicly available from Gemini Observatory with the respective programme number. It can be found under the following URL: <https://archive.gemini.edu/searchform>, selecting 'MAROON-X' from the

drop-down options under 'Instrument', and adding the programme number in the field 'Program ID'. The Programme IDs are in Extended Data Table 1, after the name of the PI and start with 'GN'. The ESPRESSO data can be downloaded directly from the ESO data archive by searching for the respective run number. The ESO data archive is available here: https://archive.eso.org/eso/eso_archive_main.html, selecting the instrument 'ESPRESSO' with a tick mark, and adding the programme number (same location as for MAROON-X but starts with a number) to the search field "Programme ID". Then click 'search', select the data, and download the raw data for individual processing, or the reduced data for the direct science products. The data in the figures has been released here: [10.5281/zenodo.19392474](https://doi.org/10.5281/zenodo.19392474).

- Code availability: The cross-correlation analysis code `tayph` which embeds the data preparation, cross-correlation and extraction of the velocity is publicly available here: <https://github.com/Hoeijmakers/tayph>. `molecfi` is a standard ESO software embedded in ESOReflex and publicly available here: <https://www.eso.org/sci/software/pipelines/skytools/molecfi>.
- Acknowledgements: We would like to thank the anonymous referees and Daniele Viganò for their valuable inputs which have greatly increased the robustness of our conclusions and the impact of the presented work. The authors acknowledge the ESPRESSO project team for its effort and dedication in building the ESPRESSO instrument, as well as the project team and support staff of MAROON-X. This work relied on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere and at the international Gemini Observatory, a program of NSF NOIRLab, which is managed by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the U.S. National Science Foundation, on behalf of the Gemini partnership of Argentina, Brazil, Canada, Chile, the Republic of Korea, and the United States of America. This work was enabled by observations made from the Gemini North telescope, located within the Maunakea Science Reserve and adjacent to the summit of Maunakea. We are grateful for the privilege of observing the Universe from a place that is unique in both its astronomical quality and its cultural significance. JVS gratefully acknowledges the financial support of the Observatoire de la Côte d'Azur via the Poincaré fellowship, as well as the MERAC foundation. This work was funded by the French National Research Agency (ANR) project EXOWINDS (ANR-23-CE31-0001-01)(VP). BP acknowledges financial support of the Walter Gyllenberg Foundation for computational resources and for funding the research stay that made this project possible. BT acknowledges the financial support from the Wenner-Gren Foundation (WGF2022-0041)(BT). JPW acknowledges support from the Trottier Family Foundation via the Trottier Postdoctoral Fellowship, Swiss National Science Foundation (SNSF) under grant 10002706 (JPW) and from the Canadian Space Agency (CSA) under grant 24JWGO3A-03 (JPW). SP acknowledges support from the Swiss National Science Foundation under grant 51NF40.205606 (SP) within the framework of the National Centre of Competence in Research PlanetS. EKHL is supported by the CSH through the Bernoulli Fellowship. D.D.B.K. acknowledges support from the National Natural Science Foundation of China (NSFC) under grant 12473064 (DDBK). J.M.D acknowledges support from the research program

VIDI New Frontiers in Exoplanetary Climatology with project number 614.001.601 (JMD.), which is (partly) financed by the Dutch Research Council (NWO).

- Author contribution: JVS led the project, including the data acquisition and selection, the data analysis, as well as the modelling work, interpretation, and elaboration of the manuscript. VP has lead the observing proposal for the MAROON-X programme and devised the scientific question. He was instrumental for the overall modelling strategy, as well as contributed to the manuscript writing and general editing. BP led the cross-correlation analysis, and was instrumental in the telluric correction, post-processing, fit of the systemic velocity and in writing the manuscript. TH provided the GCM estimates. NM provided the ionisation tables. VdL benchmarked the contribution function approach and provided additional caveats. BT gave insights into the measurement of the system velocity for fast rotating host stars. KB was instrumental in the initial discussion of magnetic field strength impacts and trends. TG aided the interpretation in relation to the Solar System. RvdB advised on the methods of calculating contribution functions for cross correlation. FD provided data and important feedback on the manuscript. HB provided insights into magnetic field theories and MHD GCMs. JLB is the PI of MAROON-X and supervised the data collection and reduction. BB contributed to initial survey design and proposal and provided detailed comments on the manuscript. MB provided key insights in the interpretation and uncertainty assessment. PD benchmarked various GCM assumptions. SG, MH, EL, PS, JW, KBS, JMLBD contributed to the initial survey proposal and provided extensive commentary. DK performed MAROON-X observations and data reduction prior to July 2023. DDBK and TK advised on the theoretical interpretation and limitations of the underlying heat engine model. LP was instrumental in the uncertainty estimate and overall commentary. SP contributed to the target selection, preparation of observing proposals, and planning of observations. ER provided input on the original proposal for the data and comments on the manuscript. AS conducted some of the observations and reduced the data MAROON-X Data (2020-2022). AS provided benchmarking for the data analysis.
- Conflict of interest/Competing interests: The authors declare no competing interests.

Figure Legends/Captions (for main text figures). Caption Figure 1: A clear trend of decreasing wind speeds with equilibrium temperature. We show day-to-night line of sight wind speeds for the available population of ultra-hot Jupiters as measured from iron with a clear decrease in wind velocity as a function of equilibrium temperature. The uncertainty of the equilibrium temperature is the error propagation of the effective temperature of the star and the stellar radius to semi-major axis ratio in the calculation of the planet’s equilibrium temperature. The uncertainty on the wind speed is the fit uncertainty of the observed cross-correlation peak, taking into account the photon noise of the data, as well as the propagated uncertainty of the system velocity measurement.

Caption Figure 2: Ohmic drag models reproduce the observed trend of decreasing velocities. We show the measured velocities as data points with the Ohmic drag models for ultra-hot Jupiters colour coded at different atmospheric magnetic field strengths.

For comparison the classical models only invoking shear instabilities (dashed) or shocks (sound speed, dashed dotted) to dissipate kinetic energy are shown. The data points and uncertainties are taken from Figure 1.

Caption Figure 3: Ultra-hot Jupiters have maximum atmospheric magnetic field strength compatible with Jovian values. We show the derived maximum atmospheric magnetic field strength as a function of equilibrium temperature with the values derived with uncertainties through error propagation from the data in Figure 1. Additionally, we provide the main impacts that could create deviations on the absolute atmospheric magnetic field strength, notably order of magnitude deviations in pressure, the maximum deviation from the equilibrium temperature, and an underestimation of the absolute wind speed velocity from the line of sight measurement. The cumulative impact of all these effects is marked with a dark cross. These are order-of-magnitude estimates of the average atmospheric field in the equatorial regions, including both the deep-seated dynamo field and the field induced by the atmospheric flow.

References

- [1] Connerney, J. E. P. *et al.* A New Model of Jupiter’s Magnetic Field From Juno’s First Nine Orbits. *Geophysical Research Letters* **45**, 2590–2596 (2018). URL <https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2018GL077312>.
- [2] Liu, J. & Schneider, T. Mechanisms of Jet Formation on the Giant Planets. *Journal of the Atmospheric Sciences* **67**, 3652–3672 (2010). URL <https://journals.ametsoc.org/doi/10.1175/2010JAS3492.1>.
- [3] Kaspi, Y. *et al.* Jupiter’s atmospheric jet streams extend thousands of kilometres deep. *Nature* **555**, 223–226 (2018). URL <https://www.nature.com/articles/nature25793>.
- [4] Batygin, K. & Stevenson, D. J. Inflating Hot Jupiters with Ohmic Dissipation. *The Astrophysical Journal Letters, Volume 714, Issue 2, pp. L238-L243 (2010)*. **714**, L238 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010ApJ...714L.238B/abstract>.
- [5] Perna, R., Menou, K. & Rauscher, E. Ohmic Dissipation in the Atmospheres of Hot Jupiters. *The Astrophysical Journal, Volume 724, Issue 1, pp. 313-317 (2010)*. **724**, 313 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010ApJ...724..313P/abstract>.
- [6] Christensen, U. R., Holzwarth, V. & Reiners, A. Energy flux determines magnetic field strength of planets and stars. *Nature, Volume 457, Issue 7226, pp. 167-169 (2009)*. **457**, 167 (2009). URL <https://ui.adsabs.harvard.edu/abs/2009Natur.457..167C/abstract>.

- [7] Yadav, R. K. & Thorngren, D. P. Estimating the Magnetic Field Strength in Hot Jupiters. *The Astrophysical Journal Letters* **849**, L12 (2017). URL <https://iopscience.iop.org/article/10.3847/2041-8213/aa93fd>.
- [8] Kilmetis, K., Vidotto, A. A., Allan, A. & Kubyshkina, D. Magnetic field evolution of hot exoplanets. *Monthly Notices of the Royal Astronomical Society* **535**, 3646–3655 (2024). URL <https://academic.oup.com/mnras/article/535/4/3646/7881581>.
- [9] Zaghou, M. & Collins, G. W. Size and Strength of Self-excited Dynamos in Jupiter-like Extrasolar Planets. *The Astrophysical Journal* **862**, 19 (2018). URL <https://iopscience.iop.org/article/10.3847/1538-4357/aac6e8>.
- [10] Elias-López, A. *et al.* Rossby Number Regime, Convection Suppression, and Dynamo-generated Magnetism in Inflated Hot Jupiters. *The Astrophysical Journal* **990**, 38 (2025). URL <https://iopscience.iop.org/article/10.3847/1538-4357/adf057>.
- [11] Viganò, D. *et al.* Inflated hot Jupiters: Inferring average atmospheric velocity via Ohmic models coupled with internal dynamo evolution. *Astronomy & Astrophysics* **701**, A8 (2025). URL <https://www.aanda.org/10.1051/0004-6361/202555219>.
- [12] Dietrich, W. *et al.* Magnetic induction processes in hot Jupiters, application to KELT-9b. *Monthly Notices of the Royal Astronomical Society* **517**, 3113–3125 (2022). URL <https://academic.oup.com/mnras/article/517/3/3113/6753224>.
- [13] Cuntz, M., Saar, S. H. & Musielak, Z. E. On Stellar Activity Enhancement Due to Interactions with Extrasolar Giant Planets. *The Astrophysical Journal, Volume 533, Issue 2, pp. L151-L154.* **533**, L151 (2000). URL <https://ui.adsabs.harvard.edu/abs/2000ApJ...533L.151C/abstract>.
- [14] Shkolnik, E., Walker, G. a. H. & Bohlender, D. A. Evidence for Planet-induced Chromospheric Activity on HD 179949. *The Astrophysical Journal, Volume 597, Issue 2, pp. 1092-1096.* **597**, 1092 (2003). URL <https://ui.adsabs.harvard.edu/abs/2003ApJ...597.1092S/abstract>.
- [15] Shkolnik, E., Walker, G. a. H., Bohlender, D. A., Gu, P.-G. & Kürster, M. Hot Jupiters and Hot Spots: The Short- and Long-Term Chromospheric Activity on Stars with Giant Planets. *The Astrophysical Journal, Volume 622, Issue 2, pp. 1075-1090.* **622**, 1075 (2005). URL <https://ui.adsabs.harvard.edu/abs/2005ApJ...622.1075S/abstract>.
- [16] Shkolnik, E. *et al.* Star-Planet Interactions **1094**, 275–282 (2009). URL <https://ui.adsabs.harvard.edu/abs/2009AIPC.1094..275S>. Conference Name: 15th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun Place: eprint: arXiv:0809.4482 ADS Bibcode: 2009AIPC.1094..275S.

- [17] Cauley, P. W., Shkolnik, E. L., Llama, J. & Lanza, A. F. Magnetic field strengths of hot Jupiters from signals of star-planet interactions. *Nature Astronomy* **3**, 1128–1134 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019NatAs...3.1128C>. ADS Bibcode: 2019NatAs...3.1128C.
- [18] Cauley, P. W. & Ahlers, J. P. The Effects of Stellar Gravity Darkening on High-resolution Transmission Spectra. *The Astronomical Journal* **163**, 122 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022AJ....163..122C>. ADS Bibcode: 2022AJ....163..122C.
- [19] Vidotto, A. A., Jardine, M. & Helling, C. Early UV Ingress in WASP-12b: Measuring Planetary Magnetic Fields. *The Astrophysical Journal Letters, Volume 722, Issue 2, pp. L168-L172* (2010). **722**, L168 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010ApJ...722L.168V/abstract>.
- [20] Vidotto, A. A., Jardine, M. & Helling, C. Prospects for detection of exoplanet magnetic fields through bow-shock observations during transits. *Monthly Notices of the Royal Astronomical Society: Letters, Volume 411, Issue 1, pp. L46-L50*. **411**, L46 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011MNRAS.411L..46V/abstract>.
- [21] Llama, J. *et al.* The shocking transit of WASP-12b: modelling the observed early ingress in the near-ultraviolet. *Monthly Notices of the Royal Astronomical Society: Letters, Volume 416, Issue 1, pp. L41-L44*. **416**, L41 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011MNRAS.416L..41L/abstract>.
- [22] Cowley, S. W. H. *et al.* Solar-wind-magnetosphere-ionosphere interactions in the Earth's plasma environment. *Science and applications of the space environment: new results and interdisciplinary connections. Papers of a Theme compiled and edited by A. J. Coates, J. L. Culhane and J. C. R. Hunt. Roy Soc of London Phil Tr A, vol. 361, Issue 1802, p.113* **361**, 113 (2003). URL <https://ui.adsabs.harvard.edu/abs/2003RSPTA.361..113C/abstract>.
- [23] Grießmeier, J.-M., Zarka, P. & Spreuw, H. Predicting low-frequency radio fluxes of known extrasolar planets. *Astronomy and Astrophysics, Volume 475, Issue 1, November III 2007, pp.359-368* **475**, 359 (2007). URL <https://ui.adsabs.harvard.edu/abs/2007A%26A...475..359G/abstract>.
- [24] Zarka, P. Plasma interactions of exoplanets with their parent star and associated radio emissions. *Planetary and Space Science, Volume 55, Issue 5, p. 598-617*. **55**, 598 (2007). URL <https://ui.adsabs.harvard.edu/abs/2007P%26SS...55..598Z/abstract>.
- [25] Zarka, P., Farrell, W., Fischer, G. & Konovalenko, A. Ground-Based and Space-Based Radio Observations of Planetary Lightning. *Space Science Reviews, Volume 137, Issue 1-4, pp. 257-269* **137**, 257 (2008). URL <https://ui.adsabs.harvard.edu/abs/2008SSRv..137..257Z/abstract>.

- [26] Turner, J. D. *et al.* The search for radio emission from the exoplanetary systems 55 Cancri, mu Andromedae, and tau Booetis using LOFAR beam-formed observations. *Astronomy & Astrophysics, Volume 645, id.A59, 28 pp.* **645**, A59 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021A%26A...645A..59T/abstract>.
- [27] Turner, J. D., Grießmeier, J.-M., Zarka, P., Zhang, X. & Mauduit, E. Follow-up LOFAR observations of the tau Boötis exoplanetary system. *Astronomy & Astrophysics, Volume 688, id.A66, 8 pp.* **688**, A66 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024A%26A...688A..66T/abstract>.
- [28] Collet, B. *et al.* A New Type of Jovian Hectometric Radiation Powered by Monoenergetic Electron Beams. *Journal of Geophysical Research: Space Physics, Volume 129, Issue 5, article id. e2024JA032422* **129**, e2024JA032422 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024JGRA..12932422C/abstract>.
- [29] Narang, M. *et al.* A uGMRT search for radio emission from planets around evolved stars. *Monthly Notices of the Royal Astronomical Society, Volume 529, Issue 2, pp.1161-1168* **529**, 1161 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024MNRAS.529.1161N/abstract>.
- [30] Zarka, P. Auroral radio emissions at the outer planets: Observations and theories. *Journal of Geophysical Research* **103**, 20159–20194 (1998). URL <https://ui.adsabs.harvard.edu/abs/1998JGR...10320159Z/abstract>.
- [31] Showman, A. P., Fortney, J. J., Lewis, N. K. & Shabram, M. Doppler Signatures of the Atmospheric Circulation on Hot Jupiters. *The Astrophysical Journal* **762**, 24 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013ApJ...762...24S/abstract>.
- [32] Showman, A. P. & Guillot, T. Atmospheric Circulation and Tides of "51Peg b-like" Planets. *Astronomy & Astrophysics* **385**, 166–180 (2002). URL <http://arxiv.org/abs/astro-ph/0202236>. ArXiv:astro-ph/0202236.
- [33] Thorngren, D. P. & Fortney, J. J. Bayesian Analysis of Hot-Jupiter Radius Anomalies: Evidence for Ohmic Dissipation? *The Astronomical Journal, Volume 155, Issue 5, article id. 214, 10 pp. (2018)*. **155**, 214 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018AJ....155..214T/abstract>.
- [34] Menou, K. Magnetic Scaling Laws for the Atmospheres of Hot Giant Exoplanets. *The Astrophysical Journal, Volume 745, Issue 2, article id. 138, 8 pp. (2012)*. **745**, 138 (2012). URL <https://ui.adsabs.harvard.edu/abs/2012ApJ...745..138M/abstract>.
- [35] Rogers, T. M. & Komacek, T. D. Magnetic Effects in Hot Jupiter Atmospheres. *The Astrophysical Journal, Volume 794, Issue 2, article id. 132, 12 pp. (2014)*. **794**, 132 (2014). URL <https://ui.adsabs.harvard.edu/abs/2014ApJ...794..132R/>

abstract.

- [36] Batygin, K., Stanley, S. & Stevenson, D. J. Magnetically Controlled Circulation on Hot Extrasolar Planets. *The Astrophysical Journal, Volume 776, Issue 1, article id. 53, 14 pp. (2013)*. **776**, 53 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013ApJ...776...53B/abstract>.
- [37] Pepe, F. *et al.* ESPRESSO at VLT. On-sky performance and first results. *Astronomy and Astrophysics* **645**, A96 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021A&A...645A..96P/abstract>.
- [38] Seifahrt, A. *et al.* On-sky commissioning of MAROON-X: a new precision radial velocity spectrograph for Gemini North. *Proceedings of the SPIE, Volume 11447, id. 114471F 21 pp. (2020)*. **11447**, 114471F (2020). URL <https://ui.adsabs.harvard.edu/abs/2020SPIE11447E..1FS/abstract>.
- [39] Ehrenreich, D. *et al.* Nightside condensation of iron in an ultrahot giant exoplanet. *Nature* **580**, 597–601 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020Natur.580..597E>. ADS Bibcode: 2020Natur.580..597E.
- [40] Seidel, J. V. *et al.* Into the storm: diving into the winds of the ultra-hot Jupiter WASP-76 b with HARPS and ESPRESSO. *Astronomy and Astrophysics* **653**, A73 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021A&A...653A..73S>. ADS Bibcode: 2021A&A...653A..73S.
- [41] Kesseli, A. Y., Beltz, H., Rauscher, E. & Snellen, I. a. G. Up, Up, and Away: Winds and Dynamical Structure as a Function of Altitude in the Ultra-hot Jupiter WASP-76b. *The Astrophysical Journal* **975**, 9 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024ApJ...975....9K/abstract>.
- [42] Nortmann, L. *et al.* CRIRES transmission spectroscopy of WASP-127b. Detection of the resolved signatures of a supersonic equatorial jet and cool poles in a hot planet (2024). URL <http://arxiv.org/abs/2404.12363>. ArXiv:2404.12363 [astro-ph].
- [43] Seidel, J. V. *et al.* Vertical structure of an exoplanet’s atmospheric jet stream. *Nature, Volume 639, Issue 8056, pp. 902-908* **639**, 902 (2025). URL <https://ui.adsabs.harvard.edu/abs/2025Natur.639..902S/abstract>.
- [44] Snellen, I. Exoplanet atmospheres at high spectral resolution (2025). URL <http://arxiv.org/abs/2505.08926>. ArXiv:2505.08926 [astro-ph].
- [45] Knierim, H., Batygin, K. & Bitsch, B. Shallowness of circulation in hot Jupiters. Advancing the Ohmic dissipation model. *Astronomy & Astrophysics, Volume 658, id.L7, 7 pp.* **658**, L7 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022A%26A...658L...7K/abstract>.

- [46] Borsa, F. *et al.* Atmospheric Rossiter-McLaughlin effect and transmission spectroscopy of WASP-121b with ESPRESSO. *Astronomy & Astrophysics* **645**, A24 (2021). URL <http://arxiv.org/abs/2011.01245>. ArXiv:2011.01245 [astro-ph].
- [47] Gandhi, S. *et al.* Retrieval Survey of Metals in Six Ultrahot Jupiters: Trends in Chemistry, Rain-out, Ionization, and Atmospheric Dynamics. *AJ* **165**, 242 (2023).
- [48] Kitzmann, D. *et al.* The Mantis network - A standard grid of templates and masks for cross-correlation analyses of ultra-hot Jupiter transmission spectra., *Astronomy & Astrophysics* **669**, A113 (2023). URL <https://www.aanda.org/articles/aa/abs/2023/01/aa42969-21/aa42969-21.html>.
- [49] Hoeijmakers, H. J. *et al.* Hot Exoplanet Atmospheres Resolved with Transit Spectroscopy (HEARTS). IV. A spectral inventory of atoms and molecules in the high-resolution transmission spectrum of WASP-121 b. *Astronomy and Astrophysics* **641**, A123 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020A&A..641A.123H/abstract>.
- [50] Kesseli, A. Y. & Snellen, I. A. G. Confirmation of Asymmetric Iron Absorption in WASP-76b with HARPS. *The Astrophysical Journal* **908**, L17 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021ApJ...908L..17K>. ADS Bibcode: 2021ApJ...908L..17K.
- [51] Simonnin, A. *et al.* Time-resolved absorption of six chemical species with MAROON-X points to a strong drag in the ultra-hot Jupiter TOI-1518 b. *A&A* **698**, A314 (2025).
- [52] Fromang, S., Leconte, J. & Heng, K. Shear-driven instabilities and shocks in the atmospheres of hot Jupiters. *Astronomy and Astrophysics* **591**, A144 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016A&A...591A.144F>. ADS Bibcode: 2016A&A...591A.144F.
- [53] Heng, K., Menou, K. & Phillipps, P. J. Atmospheric circulation of tidally locked exoplanets: a suite of benchmark tests for dynamical solvers. *Monthly Notices of the Royal Astronomical Society, Volume 413, Issue 4, pp. 2380-2402.* **413**, 2380 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011MNRAS.413.2380H/abstract>.
- [54] Watkins, C. & Cho, J. Y.-K. Gravity Waves on Hot Extrasolar Planets. I. Propagation and Interaction with the Background. *The Astrophysical Journal, Volume 714, Issue 1, pp. 904-914 (2010).* **714**, 904 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010ApJ...714..904W/abstract>.
- [55] Rogers, T. M. & Showman, A. P. Magnetohydrodynamic Simulations of the Atmosphere of HD 209458b. *The Astrophysical Journal Letters, Volume 782, Issue 1, article id. L4, 6 pp. (2014).* **782**, L4 (2014). URL <https://ui.adsabs>.

[harvard.edu/abs/2014ApJ...782L...4R/abstract](https://ui.adsabs.harvard.edu/abs/2014ApJ...782L...4R/abstract).

- [56] Emanuel, K. A. An Air-Sea Interaction Theory for Tropical Cyclones. Part I: Steady-State Maintenance. *Journal of Atmospheric Sciences*, vol. 43, Issue 6, pp. 585–605 **43**, 585 (1986). URL <https://ui.adsabs.harvard.edu/abs/1986JAtS...43..585E/abstract>.
- [57] Koll, D. D. B. & Abbot, D. S. Temperature Structure and Atmospheric Circulation of Dry Tidally Locked Rocky Exoplanets. *The Astrophysical Journal*, Volume 825, Issue 2, article id. 99, 22 pp. (2016). **825**, 99 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016ApJ...825...99K/abstract>.
- [58] Koll, D. D. B. & Komacek, T. D. Atmospheric Circulations of Hot Jupiters as Planetary Heat Engines. *The Astrophysical Journal* **853**, 133 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018ApJ...853..133K>. ADS Bibcode: 2018ApJ...853..133K.
- [59] Pelletier, S. *et al.* CRIRES+ and ESPRESSO reveal an atmosphere enriched in volatiles relative to refractories on the ultra-hot Jupiter WASP-121b (2024). URL <http://arxiv.org/abs/2410.18183>. ArXiv:2410.18183.
- [60] Smith, P. C. B. *et al.* The Roasting Marshmallows Program with IGRINS on Gemini South II – WASP-121 b has super-stellar C/O and refractory-to-volatile ratios (2024). URL <https://ui.adsabs.harvard.edu/abs/2024arXiv241019017S>. Publication Title: arXiv e-prints ADS Bibcode: 2024arXiv241019017S.
- [61] Osborn, A. & Bayliss, D. Investigating the Planet-Metallicity Correlation for Hot Jupiters. *Monthly Notices of the Royal Astronomical Society* **491**, 4481–4487 (2020). URL <http://arxiv.org/abs/1911.05830>. ArXiv:1911.05830 [astro-ph].
- [62] Soriano-Guerrero, C., Viganò, D., Perna, R., Elias-López, A. & Beltz, H. Non-ideal MHD simulations of hot Jupiter atmospheres (2025). URL <http://arxiv.org/abs/2505.14342>. ArXiv:2505.14342 [astro-ph].
- [63] Oklopčić, A., Silva, M., Montero-Camacho, P. & Hirata, C. M. Detecting Magnetic Fields in Exoplanets with Spectropolarimetry of the Helium Line at 1083 nm. *The Astrophysical Journal* **890**, 88 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020ApJ...890...88O>. ADS Bibcode: 2020ApJ...890...88O.
- [64] Khodachenko, M. L. *et al.* The impact of intrinsic magnetic field on the absorption signatures of elements probing the upper atmosphere of HD209458b. *Monthly Notices of the Royal Astronomical Society* **507**, 3626–3637 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021MNRAS.507.3626K/abstract>.
- [65] Schreyer, E., Owen, J. E., Spake, J. J., Bahroloom, Z. & Di Giampasquale, S. Using helium 10 830 Å transits to constrain planetary magnetic fields. *Monthly Notices of the Royal Astronomical Society* **527**, 5117–5130 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024MNRAS.527.5117S/abstract>.

[//ui.adsabs.harvard.edu/abs/2024MNRAS.527.5117S/abstract](https://ui.adsabs.harvard.edu/abs/2024MNRAS.527.5117S/abstract).

- [66] Savel, A. B., Beltz, H., Komacek, T. D., Tsai, S.-M. & Kempton, E. M.-R. A New Lever on Exoplanetary B Fields: Measuring Heavy Ion Velocities. *The Astrophysical Journal Letters*, Volume 969, Issue 2, id.L27, 8 pp. **969**, L27 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024ApJ...969L..27S/abstract>.
- [67] Seidel, J. V. *et al.* Detection of a high-velocity sodium feature on the ultra-hot Jupiter WASP-121 b. *Astronomy and Astrophysics* **673**, A125 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023A&A...673A.125S>. ADS Bibcode: 2023A&A...673A.125S.
- [68] Sedaghati, E. *et al.* A spectral survey of WASP-19b with ESPRESSO. *Monthly Notices of the Royal Astronomical Society* **505**, 435–458 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021MNRAS.505..435S>. ADS Bibcode: 2021MNRAS.505..435S.
- [69] Maguire, C. *et al.* High-resolution atmospheric retrievals of WASP-76b transmission spectroscopy with ESPRESSO: Monitoring limb asymmetries across multiple transits (2024). URL <http://arxiv.org/abs/2404.10463>. ArXiv:2404.10463 [astro-ph].
- [70] Pelletier, S. *et al.* Vanadium oxide and a sharp onset of cold-trapping on a giant exoplanet. *Nature* (2023). URL <http://arxiv.org/abs/2306.08739>. ArXiv:2306.08739 [astro-ph].
- [71] Maguire, C. *et al.* High-resolution atmospheric retrievals of WASP-121b transmission spectroscopy with ESPRESSO: Consistent relative abundance constraints across multiple epochs and instruments. *Monthly Notices of the Royal Astronomical Society* **519**, 1030–1048 (2022). URL <http://arxiv.org/abs/2211.09621>. ArXiv:2211.09621 [astro-ph].
- [72] Zhang, Y. *et al.* Transmission spectroscopy of the ultra-hot Jupiter MASCARA-4 b. Disentangling the hydrostatic and exospheric regimes of ultra-hot Jupiters. *Astronomy & Astrophysics*, Volume 666, id.A47, 13 pp. **666**, A47 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022A%26A...666A..47Z/abstract>.
- [73] Damasceno, Y. C. *et al.* The atmospheric composition of the ultra-hot Jupiter WASP-178 b observed with ESPRESSO (2024). URL <http://arxiv.org/abs/2406.08348>. ArXiv:2406.08348 [astro-ph].
- [74] Prinoth, B. *et al.* Time-resolved transmission spectroscopy of the ultra-hot Jupiter WASP-189 b (2023). URL <http://arxiv.org/abs/2308.04523>. ArXiv:2308.04523 [astro-ph].
- [75] Prinoth, B. *et al.* An atlas of resolved spectral features in the transmission spectrum of WASP-189 b with MAROON-X. *Astronomy & Astrophysics* (2024).

- URL <http://arxiv.org/abs/2403.08863>. ArXiv:2403.08863 [astro-ph].
- [76] Eastman, J. D. *et al.* KELT-4Ab: AN INFLATED HOT JUPITER TRANSITING THE BRIGHT ($V - 10$) COMPONENT OF A HIERARCHICAL TRIPLE. *The Astronomical Journal* **151**, 45 (2016). URL <https://iopscience.iop.org/article/10.3847/0004-6256/151/2/45>.
- [77] Stangret, M. *et al.* High-resolution transmission spectroscopy study of ultra-hot Jupiters HAT-P-57b, KELT-17b, KELT-21b, KELT-7b, MASCARA-1b, and WASP-189b. *Astronomy and Astrophysics* **662**, A101 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022A&A...662A.101S>. ADS Bibcode: 2022A&A...662A.101S.
- [78] Saffe, C. *et al.* KELT-17: a chemically peculiar Am star and a hot-Jupiter planet. *Astronomy & Astrophysics, Volume 641, id.A145, 5 pp.* **641**, A145 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020A%26A...641A.145S/abstract>.
- [79] Tan, X. & Komacek, T. D. The Atmospheric Circulation of Ultra-hot Jupiters. *The Astrophysical Journal, Volume 886, Issue 1, article id. 26, 20 pp.* (2019). **886**, 26 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019ApJ...886...26T/abstract>.
- [80] Bell, T. J. & Cowan, N. B. Increased Heat Transport in Ultra-hot Jupiter Atmospheres through H₂ Dissociation and Recombination. *The Astrophysical Journal Letters, Volume 857, Issue 2, article id. L20, 6 pp.* (2018). **857**, L20 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018ApJ...857L..20B/abstract>.
- [81] Cauley, P. W. *et al.* Time-resolved rotational velocities in the upper atmosphere of WASP-33 b. *The Astronomical Journal* **161**, 152 (2021). URL <http://arxiv.org/abs/2010.02118>. ArXiv:2010.02118 [astro-ph].
- [82] Yang, Y., Chen, G., Wang, S. & Yan, F. High-resolution transmission spectroscopy of ultra-hot Jupiter WASP-33b with NEID (2023). URL <http://arxiv.org/abs/2312.02413>. ArXiv:2312.02413 [astro-ph].
- [83] D'Arpa, M. C. *et al.* The GAPS programme at TNG LX Atmospheric characterisation of KELT-9 b via single-line analysis: Detection of six H I Balmer lines, Na I, Ca I, Ca II, Fe I, Fe II, Mg I, Ti II, Sc II, and Cr II (2024). URL <http://arxiv.org/abs/2409.01779>. ArXiv:2409.01779 [astro-ph].
- [84] Borsa, F. *et al.* The GAPS Programme with HARPS-N at TNG - XIX. Atmospheric Rossiter-McLaughlin effect and improved parameters of KELT-9b. *Astronomy & Astrophysics* **631**, A34 (2019). URL <https://www.aanda.org/articles/aa/abs/2019/11/aa35718-19/aa35718-19.html>.

- [85] Smette, A. *et al.* Molecfit: A general tool for telluric absorption correction. I. Method and application to ESO instruments. *Astronomy and Astrophysics* **576**, A77 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015A&A...576A..77S>. ADS Bibcode: 2015A&A...576A..77S.
- [86] Kausch, W. *et al.* Molecfit: A general tool for telluric absorption correction II. Quantitative evaluation on ESO-VLT X-Shooter spectra. *Astronomy & Astrophysics* **576**, A78 (2015). URL <http://arxiv.org/abs/1501.07265>. ArXiv:1501.07265 [astro-ph].
- [87] Borsato, N. W. *et al.* The Mantis Network III: Expanding the limits of chemical searches within ultra hot-Jupiters. New detections of Ca I, V I, Ti I, Cr I, Ni I, Sr II, Ba II, and Tb II in KELT-9 b (2023). URL <http://arxiv.org/abs/2304.04285>. ArXiv:2304.04285 [astro-ph].
- [88] Snellen, I. A. G., de Kok, R. J., de Mooij, E. J. W. & Albrecht, S. The orbital motion, absolute mass and high-altitude winds of exoplanet HD209458b. *Nature*, Volume 465, Issue 7301, pp. 1049-1051 (2010). **465**, 1049 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010Natur.465.1049S/abstract>.
- [89] Prinoth, B. *et al.* Titanium oxide and chemical inhomogeneity in the atmosphere of the exoplanet WASP-189 b. *Nature Astronomy* **6**, 449–457 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022NatAs...6..449P>. ADS Bibcode: 2022NatAs...6..449P.
- [90] Hoeijmakers, H. J. *et al.* The Mantis Network. IV. A titanium cold trap on the ultra-hot Jupiter WASP-121 b. *Astronomy and Astrophysics* **685**, A139 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024A&A...685A.139H>. ADS Bibcode: 2024A&A...685A.139H.
- [91] Cegla, H. M. *et al.* The Rossiter-McLaughlin effect reloaded: Probing the 3D spin-orbit geometry, differential stellar rotation, and the spatially-resolved stellar spectrum of star-planet systems. *Astronomy and Astrophysics* **588**, A127 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016A&A...588A.127C>. ADS Bibcode: 2016A&A...588A.127C.
- [92] Patel, J. A. & Espinoza, N. Empirical Limb-darkening Coefficients and Transit Parameters of Known Exoplanets from TESS. *The Astronomical Journal*, Volume 163, Issue 5, id.228, 24 pp. **163**, 228 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022AJ....163..228P/abstract>.
- [93] Saha, S. Precise Transit Photometry Using TESS: Updated Physical Properties for 28 Exoplanets around Bright Stars. *The Astrophysical Journal Supplement Series*, Volume 268, Issue 1, id.2, 17 pp. **268**, 2 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023ApJS..268....2S/abstract>.

- [94] Pagano, I. *et al.* Constraining the reflective properties of WASP-178b using Cheops photometry (2023). URL <http://arxiv.org/abs/2309.09037>. ArXiv:2309.09037 [astro-ph].
- [95] Gray, D. F. *The Observation and Analysis of Stellar Photospheres* (2008). URL <https://ui.adsabs.harvard.edu/abs/2008oasp.book.....G>. Publication Title: The Observation and Analysis of Stellar Photospheres ADS Bibcode: 2008oasp.book.....G.
- [96] Husser, T.-O. *et al.* A new extensive library of PHOENIX stellar atmospheres and synthetic spectra. *Astronomy & Astrophysics* **553**, A6 (2013). URL <http://arxiv.org/abs/1303.5632>. ArXiv:1303.5632 [astro-ph].
- [97] Buchner, J. PyMultiNest: Python interface for MultiNest. *Astrophysics Source Code Library* ascl:1606.005 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016ascl.soft06005B>. ADS Bibcode: 2016ascl.soft06005B.
- [98] Cabot, S. H. C. *et al.* TOI-1518b: A Misaligned Ultra-hot Jupiter with Iron in Its Atmosphere. *The Astronomical Journal* **162**, 218 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021AJ....162..218C/abstract>.
- [99] Zhou, G. *et al.* HATS-70b: A 13 MJ Brown Dwarf Transiting an A Star. *The Astronomical Journal* **157**, 31 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019AJ....157...31Z/abstract>.
- [100] Lenhart, C. *et al.* PEPSI Investigation, Retrieval, and Atlas of Numerous Giant Atmospheres (PIRANGA). II. Phase-Resolved Cross-Correlation Transmission Spectroscopy of KELT-20b (2025). URL <https://arxiv.org/abs/2503.07719>.
- [101] Basinger, C. *et al.* PEPSI investigation, retrieval, and atlas of numerous giant atmospheres (PIRANGA) – III. Composition and winds in the atmosphere of TOI-1518 b. *Monthly Notices of the Royal Astronomical Society* **543**, 4136–4143 (2025). URL <https://academic.oup.com/mnras/article/543/4/4136/8266785>.
- [102] Rauscher, E. & Menou, K. Three-dimensional Atmospheric Circulation Models of HD 189733b and HD 209458b with Consistent Magnetic Drag and Ohmic Dissipation. *The Astrophysical Journal, Volume 764, Issue 1, article id. 103, 18 pp. (2013)*. **764**, 103 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013ApJ...764..103R/abstract>.
- [103] Beltz, H., Rauscher, E., Kempton, E. M. R., Malsky, I. & Savel, A. B. Magnetic Effects and 3D Structure in Theoretical High-resolution Transmission Spectra of Ultrahot Jupiters: the Case of WASP-76b. *The Astronomical Journal* **165**, 257 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023AJ....165..257B>. ADS Bibcode: 2023AJ....165..257B.

- [104] Christie, D. A., Evans-Soma, T. M., Mayne, N. J. & Kohary, K. Geometric Considerations in Hot Jupiter Magnetic Drag Models (2025). URL <http://arxiv.org/abs/2507.08511>. ArXiv:2507.08511 [astro-ph].
- [105] Beltz, H. *et al.* The Effects of Kinematic Magnetohydrodynamics on the Atmospheric Circulation of Eccentric Hot Jupiters. *The Astrophysical Journal*, Volume 984, Issue 1, id.90, 18 pp. **984**, 90 (2025). URL <https://ui.adsabs.harvard.edu/abs/2025ApJ...984...90B/abstract>.
- [106] Draine, B. T., Roberge, W. G. & Dalgarno, A. Magnetohydrodynamic shock waves in molecular clouds. *The Astrophysical Journal* **264**, 485 (1983). URL <http://adsabs.harvard.edu/doi/10.1086/160617>.
- [107] Lupu, R., Freedman, R., Gharib-Nezhad, E., Visscher, C. & Molliere, P. Correlated k coefficients for H₂-He atmospheres; 11 spectral windows and 1460 pressure-temperature points (2021). URL <https://zenodo.org/records/7542048>.
- [108] Visscher, C., Lodders, K. & Fegley, B. ATMOSPHERIC CHEMISTRY IN GIANT PLANETS, BROWN DWARFS, AND LOW-MASS DWARF STARS. III. IRON, MAGNESIUM, AND SILICON. *The Astrophysical Journal* **716**, 1060–1075 (2010). URL <https://iopscience.iop.org/article/10.1088/0004-637X/716/2/1060>.
- [109] Batygin, K., Stevenson, D. J. & Bodenheimer, P. H. Evolution of Ohmically Heated Hot Jupiters. *The Astrophysical Journal*, Volume 738, Issue 1, article id. 1, 10 pp. (2011). **738**, 1 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011ApJ...738....1B/abstract>.
- [110] Heng, K. The Influence of Atmospheric Scattering and Absorption on Ohmic Dissipation in Hot Jupiters. *The Astrophysical Journal* **748**, L17 (2012). URL <https://ui.adsabs.harvard.edu/abs/2012ApJ...748L..17H>. ADS Bibcode: 2012ApJ...748L..17H.
- [111] Balbus, S. A. & Hawley, J. F. Solar Nebula Magnetohydrodynamics. *Space Science Reviews*, v. 92, Issue 1/2, p. 39-54 (2000). **92**, 39 (2000). URL <https://ui.adsabs.harvard.edu/abs/2000SSRv...92...39B/abstract>.
- [112] Komacek, T. D., Showman, A. P. & Tan, X. Atmospheric Circulation of Hot Jupiters: Dayside-Nightside Temperature Differences. II. Comparison with Observations. *The Astrophysical Journal*, Volume 835, Issue 2, article id. 198, 14 pp. (2017). **835**, 198 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017ApJ...835..198K/abstract>.
- [113] Adcroft, A., Campin, J.-M., Hill, C. & Marshall, J. Implementation of an Atmosphere Ocean General Circulation Model on the Expanded Spherical Cube. *Monthly Weather Review*, vol. 132, issue 12, p. 2845 **132**, 2845 (2004). URL <https://ui.adsabs.harvard.edu/abs/2004MWRv..132.2845A/abstract>.

- [114] Showman, A. P. *et al.* Atmospheric Circulation of Hot Jupiters: Coupled Radiative-Dynamical General Circulation Model Simulations of HD 189733b and HD 209458b. *The Astrophysical Journal*, Volume 699, Issue 1, pp. 564-584 (2009). **699**, 564 (2009). URL <https://ui.adsabs.harvard.edu/abs/2009ApJ...699..564S/abstract>.
- [115] Roth, A., Parmentier, V. & Hammond, M. Hot Jupiter diversity and the onset of TiO/VO revealed by a large grid of non-grey global circulation models. *Monthly Notices of the Royal Astronomical Society*, Volume 531, Issue 1, pp.1056-1083 **531**, 1056 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024MNRAS.531.1056R/abstract>.
- [116] Marley, M. S. & McKay, C. P. Thermal Structure of Uranus' Atmosphere. *Icarus*, Volume 138, Issue 2, pp. 268-286. **138**, 268 (1999). URL <https://ui.adsabs.harvard.edu/abs/1999Icar..138..268M/abstract>.
- [117] Mollière, P. *et al.* petitRADTRANS. A Python radiative transfer package for exoplanet characterization and retrieval. *Astronomy and Astrophysics* **627**, A67 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019A&A...627A..67M>. ADS Bibcode: 2019A&A...627A..67M.
- [118] Parmentier, V. *et al.* From thermal dissociation to condensation in the atmospheres of ultra hot Jupiters: WASP-121b in context. *Astronomy & Astrophysics*, Volume 617, id.A110, 17 pp. **617**, A110 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018A%26A...617A.110P/abstract>.

References

- [1] Connerney, J. E. P. *et al.* A New Model of Jupiter's Magnetic Field From Juno's First Nine Orbits. *Geophysical Research Letters* **45**, 2590–2596 (2018). URL <https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2018GL077312>.
- [2] Liu, J. & Schneider, T. Mechanisms of Jet Formation on the Giant Planets. *Journal of the Atmospheric Sciences* **67**, 3652–3672 (2010). URL <https://journals.ametsoc.org/doi/10.1175/2010JAS3492.1>.
- [3] Kaspi, Y. *et al.* Jupiter's atmospheric jet streams extend thousands of kilometres deep. *Nature* **555**, 223–226 (2018). URL <https://www.nature.com/articles/nature25793>.
- [4] Batygin, K. & Stevenson, D. J. Inflating Hot Jupiters with Ohmic Dissipation. *The Astrophysical Journal Letters*, Volume 714, Issue 2, pp. L238-L243 (2010). **714**, L238 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010ApJ...714L.238B/abstract>.

- [5] Perna, R., Menou, K. & Rauscher, E. Ohmic Dissipation in the Atmospheres of Hot Jupiters. *The Astrophysical Journal*, Volume 724, Issue 1, pp. 313-317 (2010). **724**, 313 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010ApJ...724..313P/abstract>.
- [6] Christensen, U. R., Holzwarth, V. & Reiners, A. Energy flux determines magnetic field strength of planets and stars. *Nature*, Volume 457, Issue 7226, pp. 167-169 (2009). **457**, 167 (2009). URL <https://ui.adsabs.harvard.edu/abs/2009Natur.457..167C/abstract>.
- [7] Yadav, R. K. & Thorngren, D. P. Estimating the Magnetic Field Strength in Hot Jupiters. *The Astrophysical Journal Letters* **849**, L12 (2017). URL <https://iopscience.iop.org/article/10.3847/2041-8213/aa93fd>.
- [8] Kilmetis, K., Vidotto, A. A., Allan, A. & Kubyshkina, D. Magnetic field evolution of hot exoplanets. *Monthly Notices of the Royal Astronomical Society* **535**, 3646–3655 (2024). URL <https://academic.oup.com/mnras/article/535/4/3646/7881581>.
- [9] Zaghoo, M. & Collins, G. W. Size and Strength of Self-excited Dynamos in Jupiter-like Extrasolar Planets. *The Astrophysical Journal* **862**, 19 (2018). URL <https://iopscience.iop.org/article/10.3847/1538-4357/aac6e8>.
- [10] Elias-López, A. *et al.* Rossby Number Regime, Convection Suppression, and Dynamo-generated Magnetism in Inflated Hot Jupiters. *The Astrophysical Journal* **990**, 38 (2025). URL <https://iopscience.iop.org/article/10.3847/1538-4357/adf057>.
- [11] Viganò, D. *et al.* Inflated hot Jupiters: Inferring average atmospheric velocity via Ohmic models coupled with internal dynamo evolution. *Astronomy & Astrophysics* **701**, A8 (2025). URL <https://www.aanda.org/10.1051/0004-6361/202555219>.
- [12] Dietrich, W. *et al.* Magnetic induction processes in hot Jupiters, application to KELT-9b. *Monthly Notices of the Royal Astronomical Society* **517**, 3113–3125 (2022). URL <https://academic.oup.com/mnras/article/517/3/3113/6753224>.
- [13] Cuntz, M., Saar, S. H. & Musielak, Z. E. On Stellar Activity Enhancement Due to Interactions with Extrasolar Giant Planets. *The Astrophysical Journal*, Volume 533, Issue 2, pp. L151-L154. **533**, L151 (2000). URL <https://ui.adsabs.harvard.edu/abs/2000ApJ...533L.151C/abstract>.
- [14] Shkolnik, E., Walker, G. a. H. & Bohlender, D. A. Evidence for Planet-induced Chromospheric Activity on HD 179949. *The Astrophysical Journal*, Volume 597, Issue 2, pp. 1092-1096. **597**, 1092 (2003). URL <https://ui.adsabs.harvard.edu/abs/2003ApJ...597.1092S/abstract>.

- [15] Shkolnik, E., Walker, G. a. H., Bohlender, D. A., Gu, P.-G. & Kürster, M. Hot Jupiters and Hot Spots: The Short- and Long-Term Chromospheric Activity on Stars with Giant Planets. *The Astrophysical Journal*, Volume 622, Issue 2, pp. 1075–1090. **622**, 1075 (2005). URL <https://ui.adsabs.harvard.edu/abs/2005ApJ...622.1075S/abstract>.
- [16] Shkolnik, E. *et al.* Star-Planet Interactions **1094**, 275–282 (2009). URL <https://ui.adsabs.harvard.edu/abs/2009AIPC.1094..275S>. Conference Name: 15th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun Place: eprint: arXiv:0809.4482 ADS Bibcode: 2009AIPC.1094..275S.
- [17] Cauley, P. W., Shkolnik, E. L., Llama, J. & Lanza, A. F. Magnetic field strengths of hot Jupiters from signals of star-planet interactions. *Nature Astronomy* **3**, 1128–1134 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019NatAs...3.1128C>. ADS Bibcode: 2019NatAs...3.1128C.
- [18] Cauley, P. W. & Ahlers, J. P. The Effects of Stellar Gravity Darkening on High-resolution Transmission Spectra. *The Astronomical Journal* **163**, 122 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022AJ....163..122C>. ADS Bibcode: 2022AJ....163..122C.
- [19] Vidotto, A. A., Jardine, M. & Helling, C. Early UV Ingress in WASP-12b: Measuring Planetary Magnetic Fields. *The Astrophysical Journal Letters*, Volume 722, Issue 2, pp. L168–L172 (2010). **722**, L168 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010ApJ...722L.168V/abstract>.
- [20] Vidotto, A. A., Jardine, M. & Helling, C. Prospects for detection of exoplanet magnetic fields through bow-shock observations during transits. *Monthly Notices of the Royal Astronomical Society: Letters*, Volume 411, Issue 1, pp. L46–L50. **411**, L46 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011MNRAS.411L..46V/abstract>.
- [21] Llama, J. *et al.* The shocking transit of WASP-12b: modelling the observed early ingress in the near-ultraviolet. *Monthly Notices of the Royal Astronomical Society: Letters*, Volume 416, Issue 1, pp. L41–L44. **416**, L41 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011MNRAS.416L..41L/abstract>.
- [22] Cowley, S. W. H. *et al.* Solar-wind-magnetosphere-ionosphere interactions in the Earth’s plasma environment. *Science and applications of the space environment: new results and interdisciplinary connections. Papers of a Theme compiled and edited by A. J. Coates, J. L. Culhane and J. C. R. Hunt. Roy Soc of London Phil Tr A*, vol. 361, Issue 1802, p.113 **361**, 113 (2003). URL <https://ui.adsabs.harvard.edu/abs/2003RSPTA.361..113C/abstract>.
- [23] Grießmeier, J.-M., Zarka, P. & Spreuw, H. Predicting low-frequency radio fluxes of known extrasolar planets. *Astronomy and Astrophysics*, Volume 475, Issue 1, November III 2007, pp.359–368 **475**, 359 (2007). URL <https://ui.adsabs>.

[harvard.edu/abs/2007A%26A...475..359G/abstract](https://ui.adsabs.harvard.edu/abs/2007A%26A...475..359G/abstract).

- [24] Zarka, P. Plasma interactions of exoplanets with their parent star and associated radio emissions. *Planetary and Space Science, Volume 55, Issue 5, p. 598-617.* **55**, 598 (2007). URL <https://ui.adsabs.harvard.edu/abs/2007P%26SS...55..598Z/abstract>.
- [25] Zarka, P., Farrell, W., Fischer, G. & Konovalenko, A. Ground-Based and Space-Based Radio Observations of Planetary Lightning. *Space Science Reviews, Volume 137, Issue 1-4, pp. 257-269* **137**, 257 (2008). URL <https://ui.adsabs.harvard.edu/abs/2008SSRv..137..257Z/abstract>.
- [26] Turner, J. D. *et al.* The search for radio emission from the exoplanetary systems 55 Cancri, mu Andromedae, and tau Booetis using LOFAR beam-formed observations. *Astronomy & Astrophysics, Volume 645, id.A59, 28 pp.* **645**, A59 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021A%26A...645A..59T/abstract>.
- [27] Turner, J. D., Grießmeier, J.-M., Zarka, P., Zhang, X. & Mauduit, E. Follow-up LOFAR observations of the tau Boötis exoplanetary system. *Astronomy & Astrophysics, Volume 688, id.A66, 8 pp.* **688**, A66 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024A%26A...688A..66T/abstract>.
- [28] Collet, B. *et al.* A New Type of Jovian Hectometric Radiation Powered by Monoenergetic Electron Beams. *Journal of Geophysical Research: Space Physics, Volume 129, Issue 5, article id. e2024JA032422* **129**, e2024JA032422 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024JGRA..12932422C/abstract>.
- [29] Narang, M. *et al.* A uGMRT search for radio emission from planets around evolved stars. *Monthly Notices of the Royal Astronomical Society, Volume 529, Issue 2, pp.1161-1168* **529**, 1161 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024MNRAS.529.1161N/abstract>.
- [30] Zarka, P. Auroral radio emissions at the outer planets: Observations and theories. *Journal of Geophysical Research* **103**, 20159–20194 (1998). URL <https://ui.adsabs.harvard.edu/abs/1998JGR...10320159Z/abstract>.
- [31] Showman, A. P., Fortney, J. J., Lewis, N. K. & Shabram, M. Doppler Signatures of the Atmospheric Circulation on Hot Jupiters. *The Astrophysical Journal* **762**, 24 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013ApJ...762...24S/abstract>.
- [32] Showman, A. P. & Guillot, T. Atmospheric Circulation and Tides of "51Peg b-like" Planets. *Astronomy & Astrophysics* **385**, 166–180 (2002). URL <http://arxiv.org/abs/astro-ph/0202236>. ArXiv:astro-ph/0202236.

- [33] Thorngren, D. P. & Fortney, J. J. Bayesian Analysis of Hot-Jupiter Radius Anomalies: Evidence for Ohmic Dissipation? *The Astronomical Journal*, Volume 155, Issue 5, article id. 214, 10 pp. (2018). **155**, 214 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018AJ....155..214T/abstract>.
- [34] Menou, K. Magnetic Scaling Laws for the Atmospheres of Hot Giant Exoplanets. *The Astrophysical Journal*, Volume 745, Issue 2, article id. 138, 8 pp. (2012). **745**, 138 (2012). URL <https://ui.adsabs.harvard.edu/abs/2012ApJ...745..138M/abstract>.
- [35] Rogers, T. M. & Komacek, T. D. Magnetic Effects in Hot Jupiter Atmospheres. *The Astrophysical Journal*, Volume 794, Issue 2, article id. 132, 12 pp. (2014). **794**, 132 (2014). URL <https://ui.adsabs.harvard.edu/abs/2014ApJ...794..132R/abstract>.
- [36] Batygin, K., Stanley, S. & Stevenson, D. J. Magnetically Controlled Circulation on Hot Extrasolar Planets. *The Astrophysical Journal*, Volume 776, Issue 1, article id. 53, 14 pp. (2013). **776**, 53 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013ApJ...776...53B/abstract>.
- [37] Pepe, F. *et al.* ESPRESSO at VLT. On-sky performance and first results. *Astronomy and Astrophysics* **645**, A96 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021A&A...645A..96P/abstract>.
- [38] Seifahrt, A. *et al.* On-sky commissioning of MAROON-X: a new precision radial velocity spectrograph for Gemini North. *Proceedings of the SPIE*, Volume 11447, id. 114471F 21 pp. (2020). **11447**, 114471F (2020). URL <https://ui.adsabs.harvard.edu/abs/2020SPIE11447E..1FS/abstract>.
- [39] Ehrenreich, D. *et al.* Nightside condensation of iron in an ultrahot giant exoplanet. *Nature* **580**, 597–601 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020Natur.580..597E>. ADS Bibcode: 2020Natur.580..597E.
- [40] Seidel, J. V. *et al.* Into the storm: diving into the winds of the ultra-hot Jupiter WASP-76 b with HARPS and ESPRESSO. *Astronomy and Astrophysics* **653**, A73 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021A&A...653A..73S>. ADS Bibcode: 2021A&A...653A..73S.
- [41] Kesseli, A. Y., Beltz, H., Rauscher, E. & Snellen, I. a. G. Up, Up, and Away: Winds and Dynamical Structure as a Function of Altitude in the Ultra-hot Jupiter WASP-76b. *The Astrophysical Journal* **975**, 9 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024ApJ...975....9K/abstract>.
- [42] Nortmann, L. *et al.* CRISP transmission spectroscopy of WASP-127b. Detection of the resolved signatures of a supersonic equatorial jet and cool poles in a hot planet (2024). URL <http://arxiv.org/abs/2404.12363>. ArXiv:2404.12363 [astro-ph].

- [43] Seidel, J. V. *et al.* Vertical structure of an exoplanet’s atmospheric jet stream. *Nature*, Volume 639, Issue 8056, pp. 902-908 **639**, 902 (2025). URL <https://ui.adsabs.harvard.edu/abs/2025Natur.639..902S/abstract>.
- [44] Snellen, I. Exoplanet atmospheres at high spectral resolution (2025). URL <http://arxiv.org/abs/2505.08926>. ArXiv:2505.08926 [astro-ph].
- [45] Knierim, H., Batygin, K. & Bitsch, B. Shallowness of circulation in hot Jupiters. Advancing the Ohmic dissipation model. *Astronomy & Astrophysics*, Volume 658, id.L7, 7 pp. **658**, L7 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022A%26A...658L...7K/abstract>.
- [46] Borsa, F. *et al.* Atmospheric Rossiter-McLaughlin effect and transmission spectroscopy of WASP-121b with ESPRESSO. *Astronomy & Astrophysics* **645**, A24 (2021). URL <http://arxiv.org/abs/2011.01245>. ArXiv:2011.01245 [astro-ph].
- [47] Gandhi, S. *et al.* Retrieval Survey of Metals in Six Ultrahot Jupiters: Trends in Chemistry, Rain-out, Ionization, and Atmospheric Dynamics. *AJ* **165**, 242 (2023).
- [48] Kitzmann, D. *et al.* The Mantis network - A standard grid of templates and masks for cross-correlation analyses of ultra-hot Jupiter transmission spectra., *Astronomy & Astrophysics* **669**, A113 (2023). URL <https://www.aanda.org/articles/aa/abs/2023/01/aa42969-21/aa42969-21.html>.
- [49] Hoeijmakers, H. J. *et al.* Hot Exoplanet Atmospheres Resolved with Transit Spectroscopy (HEARTS). IV. A spectral inventory of atoms and molecules in the high-resolution transmission spectrum of WASP-121 b. *Astronomy and Astrophysics* **641**, A123 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020A&A...641A.123H/abstract>.
- [50] Kesseli, A. Y. & Snellen, I. A. G. Confirmation of Asymmetric Iron Absorption in WASP-76b with HARPS. *The Astrophysical Journal* **908**, L17 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021ApJ...908L..17K>. ADS Bibcode: 2021ApJ...908L..17K.
- [51] Simonnin, A. *et al.* Time-resolved absorption of six chemical species with MAROON-X points to a strong drag in the ultra-hot Jupiter TOI-1518 b. *A&A* **698**, A314 (2025).
- [52] Fromang, S., Leconte, J. & Heng, K. Shear-driven instabilities and shocks in the atmospheres of hot Jupiters. *Astronomy and Astrophysics* **591**, A144 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016A&A...591A.144F>. ADS Bibcode: 2016A&A...591A.144F.
- [53] Heng, K., Menou, K. & Phillipps, P. J. Atmospheric circulation of tidally locked exoplanets: a suite of benchmark tests for dynamical solvers. *Monthly Notices*

- of the *Royal Astronomical Society*, Volume 413, Issue 4, pp. 2380-2402. **413**, 2380 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011MNRAS.413.2380H/abstract>.
- [54] Watkins, C. & Cho, J. Y.-K. Gravity Waves on Hot Extrasolar Planets. I. Propagation and Interaction with the Background. *The Astrophysical Journal*, Volume 714, Issue 1, pp. 904-914 (2010). **714**, 904 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010ApJ...714..904W/abstract>.
- [55] Rogers, T. M. & Showman, A. P. Magnetohydrodynamic Simulations of the Atmosphere of HD 209458b. *The Astrophysical Journal Letters*, Volume 782, Issue 1, article id. L4, 6 pp. (2014). **782**, L4 (2014). URL <https://ui.adsabs.harvard.edu/abs/2014ApJ...782L...4R/abstract>.
- [56] Emanuel, K. A. An Air-Sea Interaction Theory for Tropical Cyclones. Part I: Steady-State Maintenance. *Journal of Atmospheric Sciences*, vol. 43, Issue 6, pp.585-605 **43**, 585 (1986). URL <https://ui.adsabs.harvard.edu/abs/1986JAtS...43..585E/abstract>.
- [57] Koll, D. D. B. & Abbot, D. S. Temperature Structure and Atmospheric Circulation of Dry Tidally Locked Rocky Exoplanets. *The Astrophysical Journal*, Volume 825, Issue 2, article id. 99, 22 pp. (2016). **825**, 99 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016ApJ...825...99K/abstract>.
- [58] Koll, D. D. B. & Komacek, T. D. Atmospheric Circulations of Hot Jupiters as Planetary Heat Engines. *The Astrophysical Journal* **853**, 133 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018ApJ...853..133K>. ADS Bibcode: 2018ApJ...853..133K.
- [59] Pelletier, S. *et al.* CRIRES+ and ESPRESSO reveal an atmosphere enriched in volatiles relative to refractories on the ultra-hot Jupiter WASP-121b (2024). URL <http://arxiv.org/abs/2410.18183>. ArXiv:2410.18183.
- [60] Smith, P. C. B. *et al.* The Roasting Marshmallows Program with IGRINS on Gemini South II – WASP-121 b has super-stellar C/O and refractory-to-volatile ratios (2024). URL <https://ui.adsabs.harvard.edu/abs/2024arXiv241019017S>. Publication Title: arXiv e-prints ADS Bibcode: 2024arXiv241019017S.
- [61] Osborn, A. & Bayliss, D. Investigating the Planet-Metallicity Correlation for Hot Jupiters. *Monthly Notices of the Royal Astronomical Society* **491**, 4481–4487 (2020). URL <http://arxiv.org/abs/1911.05830>. ArXiv:1911.05830 [astro-ph].
- [62] Soriano-Guerrero, C., Viganò, D., Perna, R., Elias-López, A. & Beltz, H. Non-ideal MHD simulations of hot Jupiter atmospheres (2025). URL <http://arxiv.org/abs/2505.14342>. ArXiv:2505.14342 [astro-ph].

- [63] Oklopčić, A., Silva, M., Montero-Camacho, P. & Hirata, C. M. Detecting Magnetic Fields in Exoplanets with Spectropolarimetry of the Helium Line at 1083 nm. *The Astrophysical Journal* **890**, 88 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020ApJ...890...88O>. ADS Bibcode: 2020ApJ...890...88O.
- [64] Khodachenko, M. L. *et al.* The impact of intrinsic magnetic field on the absorption signatures of elements probing the upper atmosphere of HD209458b. *Monthly Notices of the Royal Astronomical Society* **507**, 3626–3637 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021MNRAS.507.3626K/abstract>.
- [65] Schreyer, E., Owen, J. E., Spake, J. J., Bahroloom, Z. & Di Giampasquale, S. Using helium 10 830 Å transits to constrain planetary magnetic fields. *Monthly Notices of the Royal Astronomical Society* **527**, 5117–5130 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024MNRAS.527.5117S/abstract>.
- [66] Savel, A. B., Beltz, H., Komacek, T. D., Tsai, S.-M. & Kempton, E. M.-R. A New Lever on Exoplanetary B Fields: Measuring Heavy Ion Velocities. *The Astrophysical Journal Letters, Volume 969, Issue 2, id.L27, 8 pp.* **969**, L27 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024ApJ...969L..27S/abstract>.
- [67] Seidel, J. V. *et al.* Detection of a high-velocity sodium feature on the ultra-hot Jupiter WASP-121 b. *Astronomy and Astrophysics* **673**, A125 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023A&A...673A.125S>. ADS Bibcode: 2023A&A...673A.125S.
- [68] Sedaghati, E. *et al.* A spectral survey of WASP-19b with ESPRESSO. *Monthly Notices of the Royal Astronomical Society* **505**, 435–458 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021MNRAS.505..435S>. ADS Bibcode: 2021MNRAS.505..435S.
- [69] Maguire, C. *et al.* High-resolution atmospheric retrievals of WASP-76b transmission spectroscopy with ESPRESSO: Monitoring limb asymmetries across multiple transits (2024). URL <http://arxiv.org/abs/2404.10463>. ArXiv:2404.10463 [astro-ph].
- [70] Pelletier, S. *et al.* Vanadium oxide and a sharp onset of cold-trapping on a giant exoplanet. *Nature* (2023). URL <http://arxiv.org/abs/2306.08739>. ArXiv:2306.08739 [astro-ph].
- [71] Maguire, C. *et al.* High-resolution atmospheric retrievals of WASP-121b transmission spectroscopy with ESPRESSO: Consistent relative abundance constraints across multiple epochs and instruments. *Monthly Notices of the Royal Astronomical Society* **519**, 1030–1048 (2022). URL <http://arxiv.org/abs/2211.09621>. ArXiv:2211.09621 [astro-ph].
- [72] Zhang, Y. *et al.* Transmission spectroscopy of the ultra-hot Jupiter MASCARA-4 b. Disentangling the hydrostatic and exospheric regimes of ultra-hot Jupiters.

- Astronomy & Astrophysics*, Volume 666, id.A47, 13 pp. **666**, A47 (2022).
URL <https://ui.adsabs.harvard.edu/abs/2022A%26A...666A..47Z/abstract>.
- [73] Damasceno, Y. C. *et al.* The atmospheric composition of the ultra-hot Jupiter WASP-178 b observed with ESPRESSO (2024). URL <http://arxiv.org/abs/2406.08348>. ArXiv:2406.08348 [astro-ph].
- [74] Prinoth, B. *et al.* Time-resolved transmission spectroscopy of the ultra-hot Jupiter WASP-189 b (2023). URL <http://arxiv.org/abs/2308.04523>. ArXiv:2308.04523 [astro-ph].
- [75] Prinoth, B. *et al.* An atlas of resolved spectral features in the transmission spectrum of WASP-189 b with MAROON-X. *Astronomy & Astrophysics* (2024). URL <http://arxiv.org/abs/2403.08863>. ArXiv:2403.08863 [astro-ph].
- [76] Eastman, J. D. *et al.* KELT-4Ab: AN INFLATED HOT JUPITER TRANSITING THE BRIGHT (V - 10) COMPONENT OF A HIERARCHICAL TRIPLE. *The Astronomical Journal* **151**, 45 (2016). URL <https://iopscience.iop.org/article/10.3847/0004-6256/151/2/45>.
- [77] Stangret, M. *et al.* High-resolution transmission spectroscopy study of ultra-hot Jupiters HAT-P-57b, KELT-17b, KELT-21b, KELT-7b, MASCARA-1b, and WASP-189b. *Astronomy and Astrophysics* **662**, A101 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022A&A...662A.101S>. ADS Bibcode: 2022A&A...662A.101S.
- [78] Saffe, C. *et al.* KELT-17: a chemically peculiar Am star and a hot-Jupiter planet. *Astronomy & Astrophysics*, Volume 641, id.A145, 5 pp. **641**, A145 (2020). URL <https://ui.adsabs.harvard.edu/abs/2020A%26A...641A.145S/abstract>.
- [79] Tan, X. & Komacek, T. D. The Atmospheric Circulation of Ultra-hot Jupiters. *The Astrophysical Journal*, Volume 886, Issue 1, article id. 26, 20 pp. (2019). **886**, 26 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019ApJ...886...26T/abstract>.
- [80] Bell, T. J. & Cowan, N. B. Increased Heat Transport in Ultra-hot Jupiter Atmospheres through H₂ Dissociation and Recombination. *The Astrophysical Journal Letters*, Volume 857, Issue 2, article id. L20, 6 pp. (2018). **857**, L20 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018ApJ...857L..20B/abstract>.
- [81] Cauley, P. W. *et al.* Time-resolved rotational velocities in the upper atmosphere of WASP-33 b. *The Astronomical Journal* **161**, 152 (2021). URL <http://arxiv.org/abs/2010.02118>. ArXiv:2010.02118 [astro-ph].
- [82] Yang, Y., Chen, G., Wang, S. & Yan, F. High-resolution transmission spectroscopy of ultra-hot Jupiter WASP-33b with NEID (2023). URL <http://arxiv.org/abs/2308.04523>.

[org/abs/2312.02413](https://arxiv.org/abs/2312.02413). ArXiv:2312.02413 [astro-ph].

- [83] D’Arpa, M. C. *et al.* The GAPS programme at TNG LX Atmospheric characterisation of KELT-9 b via single-line analysis: Detection of six H I Balmer lines, Na I, Ca I, Ca II, Fe I, Fe II, Mg I, Ti II, Sc II, and Cr II (2024). URL <http://arxiv.org/abs/2409.01779>. ArXiv:2409.01779 [astro-ph].
- [84] Borsa, F. *et al.* The GAPS Programme with HARPS-N at TNG - XIX. Atmospheric Rossiter-McLaughlin effect and improved parameters of KELT-9b. *Astronomy & Astrophysics* **631**, A34 (2019). URL <https://www.aanda.org/articles/aa/abs/2019/11/aa35718-19/aa35718-19.html>.
- [85] Smette, A. *et al.* Molecfit: A general tool for telluric absorption correction. I. Method and application to ESO instruments. *Astronomy and Astrophysics* **576**, A77 (2015). URL <https://ui.adsabs.harvard.edu/abs/2015A&A...576A..77S>. ADS Bibcode: 2015A&A...576A..77S.
- [86] Kausch, W. *et al.* Molecfit: A general tool for telluric absorption correction II. Quantitative evaluation on ESO-VLT X-Shooter spectra. *Astronomy & Astrophysics* **576**, A78 (2015). URL <http://arxiv.org/abs/1501.07265>. ArXiv:1501.07265 [astro-ph].
- [87] Borsato, N. W. *et al.* The Mantis Network III: Expanding the limits of chemical searches within ultra hot-Jupiters. New detections of Ca I, V I, Ti I, Cr I, Ni I, Sr II, Ba II, and Tb II in KELT-9 b (2023). URL <http://arxiv.org/abs/2304.04285>. ArXiv:2304.04285 [astro-ph].
- [88] Snellen, I. A. G., de Kok, R. J., de Mooij, E. J. W. & Albrecht, S. The orbital motion, absolute mass and high-altitude winds of exoplanet HD209458b. *Nature, Volume 465, Issue 7301, pp. 1049-1051 (2010)*. **465**, 1049 (2010). URL <https://ui.adsabs.harvard.edu/abs/2010Natur.465.1049S/abstract>.
- [89] Prinoth, B. *et al.* Titanium oxide and chemical inhomogeneity in the atmosphere of the exoplanet WASP-189 b. *Nature Astronomy* **6**, 449–457 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022NatAs...6..449P>. ADS Bibcode: 2022NatAs...6..449P.
- [90] Hoeijmakers, H. J. *et al.* The Mantis Network. IV. A titanium cold trap on the ultra-hot Jupiter WASP-121 b. *Astronomy and Astrophysics* **685**, A139 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024A&A...685A.139H>. ADS Bibcode: 2024A&A...685A.139H.
- [91] Prinoth, B. *et al.* Titanium chemistry of WASP-121 b with ESPRESSO in 4-UT mode. *Astronomy & Astrophysics, Volume 694, id.A284, 14 pp.* **694**, A284 (2025). URL <https://ui.adsabs.harvard.edu/abs/2025A%26A...694A.284P/abstract>.

- [92] Cegla, H. M. *et al.* The Rossiter-McLaughlin effect reloaded: Probing the 3D spin-orbit geometry, differential stellar rotation, and the spatially-resolved stellar spectrum of star-planet systems. *Astronomy and Astrophysics* **588**, A127 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016A&A...588A.127C>. ADS Bibcode: 2016A&A...588A.127C.
- [93] Patel, J. A. & Espinoza, N. Empirical Limb-darkening Coefficients and Transit Parameters of Known Exoplanets from TESS. *The Astronomical Journal*, Volume 163, Issue 5, id.228, 24 pp. **163**, 228 (2022). URL <https://ui.adsabs.harvard.edu/abs/2022AJ....163..228P/abstract>.
- [94] Saha, S. Precise Transit Photometry Using TESS: Updated Physical Properties for 28 Exoplanets around Bright Stars. *The Astrophysical Journal Supplement Series*, Volume 268, Issue 1, id.2, 17 pp. **268**, 2 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023ApJS..268....2S/abstract>.
- [95] Pagano, I. *et al.* Constraining the reflective properties of WASP-178b using Cheops photometry (2023). URL <http://arxiv.org/abs/2309.09037>. ArXiv:2309.09037 [astro-ph].
- [96] Gray, D. F. *The Observation and Analysis of Stellar Photospheres* (2008). URL <https://ui.adsabs.harvard.edu/abs/2008oasp.book.....G>. Publication Title: The Observation and Analysis of Stellar Photospheres ADS Bibcode: 2008oasp.book.....G.
- [97] Husser, T.-O. *et al.* A new extensive library of PHOENIX stellar atmospheres and synthetic spectra. *Astronomy & Astrophysics* **553**, A6 (2013). URL <http://arxiv.org/abs/1303.5632>. ArXiv:1303.5632 [astro-ph].
- [98] Buchner, J. PyMultiNest: Python interface for MultiNest. *Astrophysics Source Code Library* ascl:1606.005 (2016). URL <https://ui.adsabs.harvard.edu/abs/2016ascl.soft06005B>. ADS Bibcode: 2016ascl.soft06005B.
- [99] Cabot, S. H. C. *et al.* TOI-1518b: A Misaligned Ultra-hot Jupiter with Iron in Its Atmosphere. *The Astronomical Journal* **162**, 218 (2021). URL <https://ui.adsabs.harvard.edu/abs/2021AJ....162..218C/abstract>.
- [100] Zhou, G. *et al.* HATS-70b: A 13 MJ Brown Dwarf Transiting an A Star. *The Astronomical Journal* **157**, 31 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019AJ....157...31Z/abstract>.
- [101] Lenhart, C. *et al.* PEPSI Investigation, Retrieval, and Atlas of Numerous Giant Atmospheres (PIRANGA). II. Phase-Resolved Cross-Correlation Transmission Spectroscopy of KELT-20b (2025). URL <https://arxiv.org/abs/2503.07719>.
- [102] Basinger, C. *et al.* PEPSI investigation, retrieval, and atlas of numerous giant atmospheres (PIRANGA) – III. Composition and winds in the atmosphere of

- TOI-1518 b. *Monthly Notices of the Royal Astronomical Society* **543**, 4136–4143 (2025). URL <https://academic.oup.com/mnras/article/543/4/4136/8266785>.
- [103] Rauscher, E. & Menou, K. Three-dimensional Atmospheric Circulation Models of HD 189733b and HD 209458b with Consistent Magnetic Drag and Ohmic Dissipation. *The Astrophysical Journal, Volume 764, Issue 1, article id. 103, 18 pp. (2013)*. **764**, 103 (2013). URL <https://ui.adsabs.harvard.edu/abs/2013ApJ...764..103R/abstract>.
- [104] Beltz, H., Rauscher, E., Kempton, E. M. R., Malsky, I. & Savel, A. B. Magnetic Effects and 3D Structure in Theoretical High-resolution Transmission Spectra of Ultrahot Jupiters: the Case of WASP-76b. *The Astronomical Journal* **165**, 257 (2023). URL <https://ui.adsabs.harvard.edu/abs/2023AJ....165..257B>. ADS Bibcode: 2023AJ....165..257B.
- [105] Christie, D. A., Evans-Soma, T. M., Mayne, N. J. & Kohary, K. Geometric Considerations in Hot Jupiter Magnetic Drag Models (2025). URL <http://arxiv.org/abs/2507.08511>. ArXiv:2507.08511 [astro-ph].
- [106] Beltz, H. *et al.* The Effects of Kinematic Magnetohydrodynamics on the Atmospheric Circulation of Eccentric Hot Jupiters. *The Astrophysical Journal, Volume 984, Issue 1, id.90, 18 pp.* **984**, 90 (2025). URL <https://ui.adsabs.harvard.edu/abs/2025ApJ...984...90B/abstract>.
- [107] Draine, B. T., Roberge, W. G. & Dalgarno, A. Magnetohydrodynamic shock waves in molecular clouds. *The Astrophysical Journal* **264**, 485 (1983). URL <http://adsabs.harvard.edu/doi/10.1086/160617>.
- [108] Lupu, R., Freedman, R., Gharib-Nezhad, E., Visscher, C. & Molliere, P. Correlated k coefficients for H₂-He atmospheres; 11 spectral windows and 1460 pressure-temperature points (2021). URL <https://zenodo.org/records/7542048>.
- [109] Visscher, C., Lodders, K. & Fegley, B. ATMOSPHERIC CHEMISTRY IN GIANT PLANETS, BROWN DWARFS, AND LOW-MASS DWARF STARS. III. IRON, MAGNESIUM, AND SILICON. *The Astrophysical Journal* **716**, 1060–1075 (2010). URL <https://iopscience.iop.org/article/10.1088/0004-637X/716/2/1060>.
- [110] Batygin, K., Stevenson, D. J. & Bodenheimer, P. H. Evolution of Ohmically Heated Hot Jupiters. *The Astrophysical Journal, Volume 738, Issue 1, article id. 1, 10 pp. (2011)*. **738**, 1 (2011). URL <https://ui.adsabs.harvard.edu/abs/2011ApJ...738....1B/abstract>.
- [111] Heng, K. The Influence of Atmospheric Scattering and Absorption on Ohmic Dissipation in Hot Jupiters. *The Astrophysical Journal* **748**, L17 (2012). URL <https://ui.adsabs.harvard.edu/abs/2012ApJ...748L..17H>. ADS Bibcode: 2012ApJ...748L..17H.

- [112] Balbus, S. A. & Hawley, J. F. Solar Nebula Magnetohydrodynamics. *Space Science Reviews*, v. 92, Issue 1/2, p. 39-54 (2000). **92**, 39 (2000). URL <https://ui.adsabs.harvard.edu/abs/2000SSRv...92...39B/abstract>.
- [113] Komacek, T. D., Showman, A. P. & Tan, X. Atmospheric Circulation of Hot Jupiters: Dayside-Nightside Temperature Differences. II. Comparison with Observations. *The Astrophysical Journal*, Volume 835, Issue 2, article id. 198, 14 pp. (2017). **835**, 198 (2017). URL <https://ui.adsabs.harvard.edu/abs/2017ApJ...835..198K/abstract>.
- [114] Adcroft, A., Campin, J.-M., Hill, C. & Marshall, J. Implementation of an Atmosphere Ocean General Circulation Model on the Expanded Spherical Cube. *Monthly Weather Review*, vol. 132, issue 12, p. 2845 **132**, 2845 (2004). URL <https://ui.adsabs.harvard.edu/abs/2004MWRv...132.2845A/abstract>.
- [115] Showman, A. P. *et al.* Atmospheric Circulation of Hot Jupiters: Coupled Radiative-Dynamical General Circulation Model Simulations of HD 189733b and HD 209458b. *The Astrophysical Journal*, Volume 699, Issue 1, pp. 564-584 (2009). **699**, 564 (2009). URL <https://ui.adsabs.harvard.edu/abs/2009ApJ...699..564S/abstract>.
- [116] Roth, A., Parmentier, V. & Hammond, M. Hot Jupiter diversity and the onset of TiO/VO revealed by a large grid of non-grey global circulation models. *Monthly Notices of the Royal Astronomical Society*, Volume 531, Issue 1, pp.1056-1083 **531**, 1056 (2024). URL <https://ui.adsabs.harvard.edu/abs/2024MNRAS.531.1056R/abstract>.
- [117] Marley, M. S. & McKay, C. P. Thermal Structure of Uranus' Atmosphere. *Icarus*, Volume 138, Issue 2, pp. 268-286. **138**, 268 (1999). URL <https://ui.adsabs.harvard.edu/abs/1999Icar..138..268M/abstract>.
- [118] Mollière, P. *et al.* petitRADTRANS. A Python radiative transfer package for exoplanet characterization and retrieval. *Astronomy and Astrophysics* **627**, A67 (2019). URL <https://ui.adsabs.harvard.edu/abs/2019A&A...627A..67M>. ADS Bibcode: 2019A&A...627A..67M.
- [119] Parmentier, V. *et al.* From thermal dissociation to condensation in the atmospheres of ultra hot Jupiters: WASP-121b in context. *Astronomy & Astrophysics*, Volume 617, id.A110, 17 pp. **617**, A110 (2018). URL <https://ui.adsabs.harvard.edu/abs/2018A%26A...617A.110P/abstract>.

Planet	Date	Inst. ^a	PI, #	S/N ^b	T _{eq} [K]	Ref.
KELT-11 b*	2024-03-31	MX	Parmentier, GN-2024A-Q-130	22.2-302.5	1712	
	2024-04-19	MX	Parmentier, GN-2024A-Q-130	22.2-297.6		
WASP-172 b*	2022-06-01	E	Albrecht, 109.22Z4.006	14.3-63.3	1740	[67]
KELT-4 A b*	2023-12-07	MX	Parmentier, GN-2023B-Q-127	28.0-82.7	1827	
	2023-12-10	MX	Parmentier, GN-2023B-Q-127	26.4-77.6		
	2023-12-16	MX	Parmentier, GN-2023B-Q-127	24.7-76.3		
	2023-12-31	MX	Parmentier, GN-2023B-Q-127	-		
WASP-173A b*	2022-07-24	E	Albrecht, 109.22Z4.003	12.4-54.9	1880	
KELT-7 b*	2023-12-28	MX	Parmentier, GN-2023B-Q-127	22.2-158.1	2048	
WASP-19 b*	2019-01-14	E	Sedaghati, 0102.C-0311	13.2-60.7	2077	[68]
	2019-03-03	E	Sedaghati, 0102.C-0311	11.8-56.1		[68]
	2019-03-22	E	Sedaghati, 0102.C-0311	13.0-66.3		[68]
	2020-01-11	E	Sedaghati, 0102.C-0311	6.8-48.9		[68]
KELT-17 b*	2020-12-25	E	Seidel, 0106.C-0126	22.7-107.2	2087	
	2021-01-31	E	Seidel, 0106.C-0126	32.0-134.9		
	2021-03-06	E	Seidel, 0106.C-0126	25.5-111.4		
WASP-76 b	2018-09-02	E	Pepe, 1102.C-0744	13.1-83.7	2229	[39]
	2018-10-30	E	Pepe, 1102.C-0744	10.5-67.5		[39]
	2019-10-18	E	Gibson, 0104.C-0642	29-55		[69]
	2020-09-03	MX	Pelletier, GN-2020B-Q-122	20.0-68.4		[70]
	2020-09-12	MX	Pelletier, GN-2020B-Q-122	17.6-63.1		[70]
	2021-10-28	MX	Debras, GN-2021B-Q-138	29.4-99.0		[70]
KELT-20 b	2023-07-07	MX	Parmentier, GN-2023A-Q-224	71.3-190.6	2263	
WASP-121 b	2021-01-26	E	Gibson, 0106.C-0516	27-37	2358	[71]
	2021-03-04	E	Gibson, 0106.C-0516	21-36		[71]
	2019-01-06	E	Pepe, 1102.C-0744	21-36		[46]
	2018-11-30	E-4UT	60.A-9128 (Comm.)	23.1-163.3		[46]
	2023-09-23	E-4UT	Seidel, 111.24J8	26.6-174.5		[43]
MASCARA-4 b*	2020-02-12	E	Wytttenbach, 0104.C-0605 300	44.9-201.7	2405	[72]
	2020-02-29	E	Wytttenbach, 0104.C-0605	46.3-207.6		[72]
WASP-178 b	2021-05-03	E	Pepe, 1104.C-0350	11.3-48.6	2398	[73]
	2021-07-09	E	Pepe, 1104.C-0350	9.3-37.7		[73]
TOI-1518 b	2022-08-13	MX	Parmentier, GN-2022B-Q-128	23.4-64.9	2491	[51]
	2023-10-19	MX	Parmentier, GN-2023B-Q-127	27.4-80.2		[51]
	2024-06-26	MX	Parmentier, GN-2024A-Q-130	24.0-65.1		[51]
HAT-P-70 b	2023-12-13	MX	Parmentier, GN-2022B-Q-128 Pelletier, GN-2022B-Q-127	22.2-64.8	2559	
	2023-12-24	MX	Parmentier, GN-2022B-Q-128 Pelletier, GN-2022B-Q-127	22.2-72.5		
WASP-189 b	2021-06-04	E	Prinoth, 107.22QF	107.7-432.6	2638	[74]
	2022-04-03	MX	Pelletier, GN-2022A-FT-208	84.1-231.6		[75]
	2022-06-02	MX	Pelletier, GN-2022A-FT-208	84.7-233.5		[75]

Extended Data Table 1 Overview of the observations. Stars mark rejected datasets. ^(a) used instruments - E: ESPRESSO, MX: MAROON-X ^(b) Minimum and maximum SNR value.