The signature of orbital motion from the dayside of the planet τ Boötis b

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The giant planet orbiting τ Boötis (named τ Boötis b) was amongst the first extrasolar planets to be discovered1. It is one of the brightest exoplanets and one of the nearest to us, with an orbital period of just a few days. Over the course of more than a decade, measurements of its orbital inclination have been announced2 and refuted3, and have hitherto remained elusive4–8. Here we report the detection of carbon monoxide absorption in the thermal dayside spectrum of τ Boötis b. At a spectral resolution of 100,000, we trace the change in the radial velocity of the planet over a large range in phase, determining that of the host star14. We cross-correlated each of the 452 extracted and processed spectra with a CO template (described in Supplementary Information section 4). We therefore adopt a circular orbit for τ Boötis b. Shown is a colour scale plot of the carbon monoxide signal as function of heliocentric (systemic) velocity (V_s) on the x axis, and the maximum radial velocity of the planet, K_p, on the left-hand y axis. The latter translates to an orbital inclination, as indicated by the scale on the right-hand y axis. Lighter colours indicate CO in absorption. A clear signal at the 6.2σ level is visible at the systemic velocity of τ Boötis b (−16.4 km s^−1), as indicated by the vertical dashed line, for a maximum orbital radial velocity of the planet of K_p = 110.0 ± 3.2 km s^−1. This corresponds to an orbital inclination i = 44.5° ± 1.5° and to a planetary mass of M_p = 5.95 ± 0.28 M_Jup. The signal is obtained by cross-correlating a template spectrum of CO lines with the CRIRES/VLT spectra, which were each shifted in wavelength using the planet’s ephemeris assuming a particular value of K_p. This to compensate for the changing Doppler effect caused by the change in the planet’s radial velocity over the large range in phase. The significance of the signal and the properties of the cross-correlated noise are discussed in Supplementary Information.

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The giant planet orbiting τ Boötis (named τ Boötis b) was amongst the first extrasolar planets to be discovered1. It is one of the brightest exoplanets and one of the nearest to us, with an orbital period of just a few days. Over the course of more than a decade, measurements of its orbital inclination have been announced2 and refuted3, and have hitherto remained elusive4–8. Here we report the detection of carbon monoxide absorption in the thermal dayside spectrum of τ Boötis b. At a spectral resolution of 100,000, we trace the change in the radial velocity of the planet over a large range in phase, determining that of the host star14. We cross-correlated each of the 452 extracted and processed spectra with a CO template (described in Supplementary Information section 4). We therefore adopt a circular orbit for τ Boötis b. Shown is a colour scale plot of the carbon monoxide signal as function of heliocentric (systemic) velocity (V_s) on the x axis, and the maximum radial velocity of the planet, K_p, on the left-hand y axis. The latter translates to an orbital inclination, as indicated by the scale on the right-hand y axis. Lighter colours indicate CO in absorption. A clear signal at the 6.2σ level is visible at the systemic velocity of τ Boötis b (−16.4 km s^−1), as indicated by the vertical dashed line, for a maximum orbital radial velocity of the planet of K_p = 110.0 ± 3.2 km s^−1. This corresponds to an orbital inclination i = 44.5° ± 1.5° and to a planetary mass of M_p = 5.95 ± 0.28 M_Jup. The signal is obtained by cross-correlating a template spectrum of CO lines with the CRIRES/VLT spectra, which were each shifted in wavelength using the planet’s ephemeris assuming a particular value of K_p. This to compensate for the changing Doppler effect caused by the change in the planet’s radial velocity over the large range in phase. The significance of the signal and the properties of the cross-correlated noise are discussed in Supplementary Information.
planet, the projected rotational velocity of the star,16 that a large fraction of the hot Jupiters around hot stars (in the plane of stellar rotation are not significantly misaligned. We point out that a system inclination of $44.5^\circ$ from 3.0 to 3.9 days from the equator to the poles. It indicates that the stellar rotation at intermediate latitudes is synchronized with the planet's orbital period ($P_i$), the planet radial's velocity with respect to the Sun and our mean solar rotation at $6\,250\,\text{K}$

$$v_{\text{rest}} (\text{km s}^{-1}) = v_\text{rot} \sin(i) \pm v_\text{rad}$$

subtracting the planet's radial velocity computed assuming a circular orbit and a similar adiabatic conditions, a CO VMR of $10^{-3}$ is required. Note that this result is consistent with the metallicity of the host star, which corresponds to a CO VMR of $10^{-3}$. We do not detect spectral features from methane or water vapour above a significance of $2\sigma$, and we use our atmospheric models to derive upper limits to the relative abundances of these molecules; we find VMR(CH$_4$)/VMR(CO) < 1 and VMR(H$_2$O)/VMR(CO) < 5 at the 90% confidence level.

Photometric observations of hot Jupiters with the Spitzer Space Telescope have been interpreted as suggestive of atmospheric thermal inversions, characterized by molecular features in emission rather than in absorption, of which HD 209458b is the best-studied example. These inversions are probably fuelled by absorption of stellar radiation in a high-altitude absorbing layer. In such a model, a thermal inversion is more likely to occur in the most highly irradiated planets, for which indeed some evidence exists. The planet τ Boötis b is more strongly irradiated than HD 209458b. However, it is clear that τ Boötis b does not exhibit a strong thermal inversion over the pressure range probed by our observations, because we see the CO signal in absorption. Although the exact pressure range probed depends on the CO abundance, the inversion layer invoked to explain the emission spectrum of HD 209458b encompasses such a wide range in atmospheric pressures that it is evident that τ Boötis b does not have an HD 209458b-type thermal inversion.

Interestingly, the host star of τ Boötis b exhibits a high level of chromospheric activity, and it has been recently suggested that hot Jupiters orbiting active stars are less likely to have thermal inversions because the strong ultraviolet radiation that accompanies chromospheric activity destroys the absorbing compound at high altitude, which would otherwise be responsible for the thermal inversion.

These observations show that high-resolution spectroscopy from the ground is a valuable tool for detailed analysis of the temperature structure and molecular content of exoplanet atmospheres. The technique that we used not only reveals its potential for transmission spectroscopy, but also for dayside spectroscopy, meaning that atmospheric characterization is no longer constrained to transiting planets alone. Detection of different molecular bands will further constrain the relative molecular abundances and $T$–$P$ profiles. In addition, tracing the absorption is visible as a dark sinusoidal trace around the systemic radial velocity of $180\,\text{km s}^{-1}$ at phase $0.37$, to $-80\,\text{km s}^{-1}$ at phase $0.63$. In b, the data are shifted to the reference frame of τ Boötis b, after subtracting the planet's radial velocity computed assuming a circular orbit and a system inclination of $44.5^\circ$. Here the planet's signal is recovered as a dark vertical trace around the planet's rest-frame velocity of $v_{\text{rest}} = 0\,\text{km s}^{-1}$. A comparison between the observed trail and artificially generated data with the same noise properties is shown in Supplementary Fig. 4.

Figure 2 | Comparison of in-trail and out-of-trail cross-correlation values.

Shown are distributions of the values of the cross-correlated time series for points in the planet's trail (grey) and out of the trail (black). The error bars denote the square root of the number of data points in each bin (1σ). The two distributions clearly deviate, with the in-trail distribution shifted to lower pixel values owing to the planet's signal. A Welch $t$-test on the data rejects the hypothesis that the two distributions are drawn from the same parent distribution at the 6σ level.

However, most of the massive planets ($M_P > 3M_{\text{Jup}}$) are found in more aligned orbits,20 and τ Boötis b does not break this trend. Our observations at high spectral resolution are only sensitive to narrow spectral features, because of the particular data reduction necessary to remove the telluric contamination. Owing to the high opacity at the wavelengths of molecular transitions, these narrow features probe the atmosphere at lower pressures than the surrounding continuum. The probed pressures are directly linked to the volume mixing ratio (VMR) of CO, but the depth of the absorption features in the emitted planetary spectrum depends on the relative temperatures at the altitudes at which the continuum and CO lines are formed. This means that there is a strong degeneracy between the temperature–pressure ($T$–$P$) profile of the planet’s atmosphere, and the VMR of CO. We compare our data with a range of models, in order to constrain the CO abundance and the $T$–$P$ profile (see Supplementary Information section 5.2). We obtain a lower limit to the CO VMR by using the adiabatic lapse rate (d$T$/d$log_P(p) \approx 1,000\,\text{K}$ at these temperatures), which is the maximum temperature gradient of a planet's atmosphere before it becomes unstable to convection. An additional uncertainty is that the size of τ Boötis b is unknown, because it is a non-transiting planet. Because the average radius of the 17 transiting hot Jupiters currently known11 with $3M_{\text{Jup}} < M_P < 9M_{\text{Jup}}$ is $1.15R_{\text{Jup}}$, we assume this value for the planet. When we set the temperature of the atmospheric layer in which the continuum is formed to $T = 2,000\,\text{K}$ (near the expected dayside equilibrium temperature for a planet without energy redistribution to the nightside), and use an adiabatic lapse rate, we require a CO VMR of $10^{-3}$ to match the observed signal. If we assume a temperature of $T = 1,650\,\text{K}$ for the continuum photospheric layer (near the dayside equilibrium temperature for a planet with perfect redistribution of energy to its nightside), under similar adiabatic conditions, a CO VMR of $10^{-4}$ is required.

Figure 3 | The orbital trail of CO absorption. a. The signature of CO in absorption is visible as a dark sinusoidal trace around the systemic radial velocity of τ Boötis, with $V_p$, the planet radial's velocity with respect to the systemic velocity, changing from $+80\,\text{km s}^{-1}$ at phase $0.37$, to $-80\,\text{km s}^{-1}$ at phase $0.63$. In b, the data are shifted to the reference frame of τ Boötis b, after subtracting the planet's radial velocity computed assuming a circular orbit and a system inclination of $44.5^\circ$: here the planet's signal is recovered as a dark vertical trace around the planet's rest-frame velocity of $v_{\text{rest}} = 0\,\text{km s}^{-1}$. A comparison between the observed trail and artificially generated data with the same noise properties is shown in Supplementary Fig. 4.
signal along the orbit will reveal the planet’s phase function, which is linked to its global atmospheric circulation. Measuring this for different molecules may reveal changes between a planet’s morning and evening spectrum driven by photochemical processes. Furthermore, molecular line profiles, in both dayside and transmission spectra, can potentially show the effects of a planet’s rotational velocity, and unveil whether these hot Jupiters are indeed tidally locked.

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1. Butler, R. P., Marcy, G. W., Williams, E., Hauser, H. & Shirts, P. Three new “51-Pegasi-type” planets. *Astrophys. J.* **474**, L115–L118 (1997).
2. Collier Cameron, A., Horne, K., Penny, A. & James, D. Probable detection of starlight reflected from the giant planet orbiting ρ Bootis. *Nature* **402**, 751–755 (1999).
3. Collier Cameron, A., Horne, K., James, D., Penny, A. & Semel, M. in *Proceedings of IAU Symposium 202: Planetary Systems in the Universe* (eds Penny, A. J., Artymowicz, P., Lagrange, A.-M. & Russell, S.) 75–77 (Astronomical Society of the Pacific, 2004).
4. Leigh, C., Collier Cameron, A., Horne, K., Penny, A. & James, D. A new upper limit on the reflected starlight from ρ Bootis b. *Mon. Not. R. Astron. Soc.* **344**, 1271–1282 (2003).
5. Charbonneau, D., Noyes, R. W., Kurzennik, S. G., Nierson, P. & Jha, S. An upper limit on the reflected light from the planet orbiting the star ρ Bootis. *Astrophys. J.* **522**, L145–L148 (1999).
6. Wiedemann, G., Deming, D. & Bjoraker, G. A sensitive search for methane in the infrared spectrum of ρ Bootis. *Astrophys. J.* **546**, 1068–1074 (2001).
7. Lucas, P. W. et al. Planetocentric polarimetry of the exoplanet systems 55 Cnc and ρ Boo. *Mon. Not. R. Astron. Soc.* **393**, 229–244 (2009).
8. Rodler, F., Kürster, M. & Henning, T. ρ Bootis b: hunting for reflected starlight. *Astron. Astrophys.* **514**, A23 (2010).
9. Burrows, A., Budaj, J. & Hubeny, I. Theoretical spectra and light curves of close-in extrasolar giant planets and comparison with data. *Astrophys. J.* **678**, 1436–1457 (2008).
10. Fortney, J. J., Lodders, K., Marley, M. S. & Freedman, R. S. A unified theory for the atmospheres of the hot and very hot Jupiters: two classes of irradiated atmospheres. *Astrophys. J.* **678**, 1419–1435 (2008).
11. Knutson, H. A., Howard, A. W. & Isaacson, H. A correlation between stellar activity and hot-Jupiter emission spectra. *Astrophys. J.* **720**, 1569–1576 (2010).
12. Kaeufl, H. U. et al. CRIRES: a high resolution infrared spectrograph for ESO’s VLT. *Proc. SPIE* **5492**, 1218–1227 (2004).
13. Snellen, I. A., de Kok, R. J., de Mooij, E. J. W. & Albrecht, S. The orbital motion, absolute mass and high-altitude winds of exoplanet HD 209458b. *Nature* **465**, 1049–1051 (2010).
14. Donati, J.-F. et al. Magnetic cycles of the planet-hosting star ρ Bootis. *Mon. Not. R. Astron. Soc.* **385**, 1179–1185 (2008).
15. Takeda, G. et al. Structure and evolution of nearby stars with planets. II. Physical properties of ~1000 cool stars from the SPOCS catalog. *Astrophys. J. Suppl. Ser.* **168**, 297–318 (2007).
16. Butler, R. P. et al. Catalog of nearby exoplanets. *Astrophys. J.* **646**, 505–522 (2006).
17. Catala, C., Donati, J.-F., Shkolnik, E., Bohlender, D. & Alecian, E. The magnetic field of the planet-hosting star ρ Bootis. *Mon. Not. R. Astron. Soc.* **374**, L42–L46 (2007).
18. Winn, J. N., Fabrycky, D., Albrecht, S. & Johnson, J. A. Hot stars with hot Jupiters have high obliquities. *Astrophys. J.* **718**, L145–L149 (2010).
19. Johnson, J. A. et al. HAT-P-30b: a transiting hot Jupiter on a highly oblique orbit. *Astrophys. J.* **735**, 24–31 (2011).
20. Hébrard, G. et al. Observation of the full 12-hour-long transit of the exoplanet HD 80606b. Warm-Spitzer photometry and SOPHIE spectroscopy. *Astron. Astrophys.* **516**, A95 (2010).
21. Schneider, J., Dedieu, C., Le Sinader, P., Savalle, R. & Zolotukhin, I. Defining and cataloguing exoplanets: the exoplanet.eu database. *Astron. Astrophys.* **532**, A79 (2011).
22. Knutson, H. A., Charbonneau, D., Burrows, A., O’Donovan, F. T. & Mandushev, G. Detection of a temperature inversion in the broadband infrared emission spectrum of TrES-4. *Astrophys. J.* **691**, 866–874 (2009).

**Supplementary Information** is linked to the online version of the paper at www.nature.com/nature.

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