Constraints on the magnetic field strength of HAT-P-7 b and other hot giant exoplanets

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Observations of the infrared and optical light curves of hot giant exoplanets have demonstrated that the peak brightness is generally offset eastwards from the substellar point1–2. This observation is consistent with hydrodynamic numerical simulations producing fast, eastwards directed winds that advect the hottest point in the atmosphere eastwards of the substellar point3–5. However, recent continuous Kepler measurements of HAT-P-7 b show that its peak brightness offset varies considerably over time, with excursions such that the brightest point is sometimes westwards of the substellar point6. These variations in brightness offset require wind variability, with or without the presence of clouds. While such wind variability has not been seen in hydrodynamic simulations of hot giant exoplanet atmospheres, it has been seen in magnetohydrodynamic simulations6. Here I show that magnetohydrodynamic simulations of HAT-P-7 b indeed display variable winds and a corresponding variability in the position of the hottest point in the atmosphere. Assuming that the observed variability in HAT-P-7 b is due to magnetism, I constrain its minimum magnetic field strength to be 6 G. Similar observations of wind variability on hot giant exoplanets, or the lack thereof, could help constrain their magnetic field strengths. As dynamo simulations of these planets do not exist and theoretical scaling relations7 may not apply, such observational constraints could prove immensely useful.

To demonstrate magnetic effects on the winds of HAT-P-7 b, I simulate the atmosphere of a hot giant exoplanet with parameters similar to HAT-P-7 b using a spherical, three-dimensional, anelastic magnetohydrodynamic (MHD) code6,8. I start with a hydrodynamic simulation of HD209458 b in terms of gravity, radius and rotation, but with the mean temperature (2,200 K) and day–night temperature differential (1,000 K) of HAT-P-7 b (the temperature and magnetic diffusivity profiles are shown in Supplementary Fig. 1). The strong day–night temperature differential drives strong eastwards atmospheric winds, consistent with previous simulations9,10. This simulation is run for ~100 rotation periods before a magnetic field is added, after which both the hydrodynamic and MHD simulations are run for an additional 280 rotation periods. Details of the numerical code and simulation can be found in the Methods.

The extreme temperatures of HAT-P-7 b give rise to a considerable thermal ionization of alkali metals11,12, which leads to coupling of the atmosphere to the deep-seated magnetic field13 and could also lead to an atmospheric dynamo14. The Lorentz force arising from this magnetic interaction disrupts the strong eastwards directed atmospheric winds typically seen in hydrodynamic simulations, leading to variable and even oppositely directed winds6. Figure 1 shows a time snapshot of the magnetic field lines in the simulation looking onto the east-side terminator (a corresponding video of its complex evolution and variability is available in Supplementary Video 1). The mean azimuthal velocity, averaged within 17° of the equator and over the upper 1 mbar of the simulated domain, is shown as a function of time in Fig. 2, along with the position of the hottest point in the atmosphere (also determined by an average over the same latitudes and heights). The hydrodynamic model retains a strong, eastwards jet and associated positive displacement of the hotspot throughout the simulation (dotted line in Fig. 2a,b). When a magnetic field is added, the zonal winds slow dramatically, reverse and then settle into an oscillatory pattern with a timescale of ~10^−3 s, consistent with the Alfvén time (\(t_A = \sqrt{4 \pi \rho / B} \)) (where \(B\) is the magnetic field strength, \(\lambda\) is its typical length scale and \(\rho\) is...
the density) of the imposed 10 G field and of the same order as the timescale of variability observed in HAT-P-7 b\textsuperscript{17}. Variability in the displacement of the hotspot, including negative offsets, is seen on a similar timescale.

Both the hydrodynamic and MHD models have more positive hotspot displacements than the observations. This is expected given that the waves that force super-rotation can propagate further in HD209458 b than in HAT-P-7 b before being damped\textsuperscript{18}. Therefore it would be expected that a hydrodynamic model with the gravity and rotation rate of HAT-P-7 b would show reduced hotspot displacements compared with HD209458 b; this is indeed found (Fig. 3). Although this magnetic model has some uncertainties (such as enhanced viscosity and crude radiative transfer), it naturally explains the bright spot excursions as due to changes in the thermal structure of the planet caused by variable winds. Clouds may not be necessary in this model because HAT-P-7 b is so hot that even the optical signal could be dominated by thermal emission. This model may also explain the timescale of the observed fluctuations as due to Alfvén waves. At the very least, it can provide the wind variability needed for models requiring clouds\textsuperscript{5}.

The effect of magnetism on zonal winds depends on the ratio of the magnetic to inertial terms in the momentum equation, which can be approximated as the ratio of magnetic to wave timescales \( \tau_{\text{mag}}/\tau_{\text{wave}} \), where \( \tau_{\text{mag}} = 4\pi\rho\eta/B^2 \) and \( \tau_{\text{wave}} = L/\sqrt{gH} \). Here \( \rho \) is the density, \( \eta \) is the magnetic diffusivity, \( B \) is the magnetic field strength, \( g \) is the gravity, \( L \) is the characteristic length scale of the horizontal flow and \( H \) is the depth of the atmosphere\textsuperscript{11,15}. As magnetic effects are increased, either through an increased magnetic field strength or increased conductivity, their effect on the atmospheric zonal winds progressed from little to no effect (when \( \tau_{\text{mag}} > \tau_{\text{wave}} \)), to oscillatory winds (when \( \tau_{\text{mag}} \approx \tau_{\text{wave}} \)) to completely reversed (westwards) winds (when \( \tau_{\text{mag}} < \tau_{\text{wave}} \)).

Assuming that the variable winds observed on HAT-P-7 b are due to magnetism and applying the oscillatory wind condition, it is found that \( B \sim \sqrt{4\pi\rho\eta/\tau_{\text{wave}}} \). Using the night side value of \( \eta \), HAT-P-7 b must have a minimum field strength of \( \sim 6 \) G. This value is consistent with the theoretical scaling relation based on the Elsasser number\textsuperscript{16} (\( \Lambda = 2\pi\Omega/\mu_0\eta \approx 1 \) where \( \Omega \) is the rotation rate and \( \mu_0 \) is the permeability of free space) and with the upper limit placed on WASP-12 b\textsuperscript{17} if it is assumed that it had a similar field strength.

To check this constraint, we ran additional models of HAT-P-7 b with the appropriate rotation, gravity, size and temperature\textsuperscript{18}. The temperature and magnetic diffusivity profiles for this model can be seen in Supplementary Fig. 2. After running a hydrodynamic model for 140 rotation periods, a magnetic field was added and run for an additional 15 rotation periods. Figure 3 shows the hotspot displacement for these models. The hydrodynamic model (black line) has a steady hotspot displacement of 2.8°. The MHD model with a 3 G field (red line) shows a similar, stable hotspot displacement. However, both the 10 G (blue line) and 20 G (orange line) models show wind variability ranging from about −15 to −20°. This range of displacement is more consistent with the observed brightness variations (which range from about −25 to −25°). However, clouds could also play a part in enhancing the large displacements observed by Kepler\textsuperscript{18}.

In these simulations, wind variability sets in between 3 and 10 G, consistent with the 6 G lower limit based purely on a simple timescale analysis. If the dayside magnetic diffusivity had been used instead in the estimate, the lower limit would have been \( \sim 0.6 \) G, inconsistent with our follow-up models, which show no variability at 3 G. This estimate depends only on the winds being variable and is independent of whether clouds are needed to explain the exact range of variability seen. Although these models are consistent with the 6 G lower limit, on this timescale no completely reversed winds are seen and therefore only a lower limit can be placed on the field strength. Although it may be possible to hone this constraint with more simulations, it is probably not worthwhile given the other limitations of these simulations.

The continuous observations of HAT-P-7 b\textsuperscript{17} were unique in that previous optical and infrared observations have generally only provided this measurement at a single epoch. The exception is the multiple epoch Spitzer observations of HD189733 b\textsuperscript{18}. That work showed a fairly stable, positive offset. This lack of variability...
where $\rho$ is the density, $T$ is the temperature, $\nu$ is the viscosity, $p$ is the pressure, $g$ is the gravity, $\gamma$ is the ratio of specific heats, and $\kappa$ is the magnetic diffusivity. The magnetic diffusivity is calculated as $\eta_m = \frac{\mu_0 \sigma \nu}{\kappa}$.

Equation (1) represents the continuity equation in the anelastic approximation\(^{20,21}\). This approximation allows some level of compressibility by allowing variation of the reference state, $\phi$, which varies in this model by four orders of magnitude. Equation (2) represents the conservation of magnetic flux. Equation (3) represents the conservation of momentum, including Coriolis and Lorentz forces. Here $p$ is the pressure, $g$ is gravity, $\nu$ is the strain tensor, and $\eta$ is the viscous diffusivity. Equation (4) represents the energy equation, written as a temperature equation where $T$ is the temperature perturbation, $T_e$ is the reference state temperature, $\kappa$ is the thermal diffusivity, $\rho$ is the specific heat at constant pressure, $\gamma$ is the ratio of specific heats and $h_e$ and $h_f$ are the inverse density and thermal diffusivity scale heights, respectively. This equation includes a forcing term to mimic stellar insolation (fourth term on the right-hand side, where $T_o$ is the equilibrium temperature) and an ohmic heating term (fifth term on the right-hand side). The radiative timescale in the Newtonian forcing term, $\tau_{rad}$, is a function that varies between $10^4$ s at the outermost layers to $10^6$ s at the lowest layers. All other variables take their usual meaning\(^6\).

The magnetic diffusivity $\eta$ (inverse conductivity) is a function of all space. If we separate the magnetic diffusivity into a mean ($\eta_t$) and fluctuating ($\eta_f$) component:

$$\eta(r, \theta, \phi) = \eta_t(r, \theta, \phi) + \eta_f(r, \theta, \phi)$$

Equation (5) (the magnetic diffusivity) is calculated from the initial temperature profile given by:

$$T_o(r, \theta, \phi) = T_e(r) + \Delta T_o(r) \cos \theta \cos \phi$$

where $T_e(r)$ is mean reference state temperature and $\Delta T_o(r)$ is the specified day–night temperature difference, here set to 1,000 K, and which is extrapolated logarithmically from the surface to 10 bar. Using this temperature profile, the magnetic diffusivity is calculated as $\eta = 2 \pi \frac{\Delta T}{\chi_e}$.

Both models presented have more complex dynamics than those found previously\(^{20,21}\) because they include a magnetic diffusivity (conductivity) that is a function of all space. This led to more complex field–flow interactions, particularly at the terminators (both) and even led to an atmosphere already\(^{22}\). Although it was not included here, a time-dependent conductivity could further complicate matters, particularly with regard to the thermal structure of the atmosphere.

Currently, we see more ohmic heating on the night side of the planet, which leads to a reduction in the day–night temperature gradient. Naively, if we allowed this to react back on the flow and conductivity, we would expect decreased wind driving and increased field–flow coupling—that is, we might expect wind variability at even lower magnetic field strengths.

Data availability statement. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

Methods

The MHD equations are solved in a three-dimensional, spherical geometry in the anelastic approximation\(^1\). The model solves the following equations:

$$\nabla \cdot (\sigma \nu) = 0$$

(1)

$$\nabla \cdot B = 0$$

(2)

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\sigma \nu \nu) = - \nabla p - \frac{\mu_0}{\kappa} \nabla^2 \phi$$

(3)

$$+2\nu \times \Omega + \nabla \left[ \frac{2\mu_0 \sigma^2}{3} (\nabla \cdot B) \right] + \frac{1}{\mu_0} \nabla \times (\nabla \times B)$$

Figure 3 | Hotspot displacement of simulated HAT-P-7b. The offset of the hottest point in the atmosphere as a function of time, calculated after a latitudinal average around 17° of the equator and the upper 1 mbar of the simulated domain. The black line shows the hydrodynamic model (barely visible under the other lines), the red line is for a 3 G field, the blue line is for a 10 G field and the orange line is for a 20 G field. The dotted line shows the subsatellite point. The inset shows the time behaviour after the magnetic field is added.

is consistent with little or no magnetic effect in HD189733 b, a plausible conclusion given that the low temperature of HD189733 b requires unrealistic magnetic field strengths of ~100–1,000 G to cause variability. In general, wind variability is expected in objects where field-flow coupling is strong (as measured by the ratio of magnetic and wave timescales). Therefore variability may also be predicted to be found in other hot giant exoplanets, such as WASP-19b or WASP-12b.

Although long timeline or multiple epoch observations of hot giant exoplanet phase curves have not been carried out for many objects, such a campaign, coupled with MHD models of the atmospheres of these planets, could be used to place constraints on the magnetic field strengths of hot giant exoplanets. Such constraints are rare\(^2\) and would be useful for dynamo theory, planetary evolution and interpretations of star–planet magnetic interactions\(^3\). As recently shown\(^1\), these types of constraints are already possible with Kepler, but will become more readily available with upcoming space missions such as the James Webb Space Telescope, the Characterising ExOPlanets Satellite (CHEOPS), the Transiting Exoplanet Survey Satellite (TESS) and the PLAnetary Transits and Oscillations of stars (PLATO). In particular, the James Webb Space Telescope will be able to measure infrared phase curves directly, allowing the detection of oscillations of stars (PLATO). In particular, the James Webb Space Telescope will be able to measure infrared phase curves directly, allowing the detection of oscillations of stars (PLATO).
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References

1. Knutson, H. A. et al. Multiwavelength constraints on the day–night circulation patterns of HD 189733b. *Astrophys. J.* **690**, 822–836 (2009).
2. Wong, I. et al. 3.6 and 4.5 μm Spitzer phase curves of ten highly-irradiated hot Jupiters WASP-19b and HAT-P-7b. *Astrophys. J.* **680**, 83–122 (2016).
3. Showman, A. P. & Guillot, T. Atmospheric circulation and tides of "51 Pegasi b-like" planets. *Astron. Astrophys.* **385**, 166–180 (2002).
4. Dobbs-Dixon, I. & Lin, D. N. C. Atmospheric dynamics of short-period extrasolar gas giant planets. I. Dependence of nightside temperature on opacity. *Astrophys. J.* **673**, 513–525 (2008).
5. Armstrong, D. J. et al. Variability in the atmosphere of the hot giant planet HAT-P-7b. *Nat. Astron.* **1**, 0004 (2016).
6. Rogers, T. M. & Komacek, T. Magnetic effects in hot Jupiter atmospheres. *Astrophys. J.* **794**, 132–144 (2014).
7. Christensen, U. Dynamo scaling laws and applications to the planets. *Space Sci. Rev.* **152**, 565–590 (2010).
8. Rogers, T. M. On limiting the thickness of the solar tachocline. *Astrophys. J.* **733**, 12–25 (2011).
9. Cooper, C. S. & Showman, A. P. Dynamic meteorology at the photosphere of HD 209458b. *Astrophys. J. Lett.* **629**, L45–L48 (2005).
10. Rauscher, E. & Menou, K. Three-dimensional modeling of hot Jupiter atmospheric flows. *Astrophys. J.* **714**, 1334–1342 (2010).
11. Perna, R., Menou, K. & Rauscher, E. Magnetic drag on hot Jupiter atmospheric winds. *Astrophys. J.* **719**, 1421–1426 (2010).
12. Batygin, K. & Stevenson, D. J. Inflating hot Jupiters with ohmic dissipation. *Astrophys. J. Lett.* **714**, L238–L243 (2010).
13. Menou, K. Magnetic scaling laws for the atmospheres of hot giant exoplanets. *Astrophys. J.* **745**, 138–146 (2012).
14. Rogers, T. M. & McElwaine, J. The hottest hot-Jupiters may host atmospheric dynamos. *Astrophys. J. Lett.* Preprint at https://arxiv.org/abs/1704.04197 (2017).
15. Perez-Becker, D. & Showman, A. P. Atmospheric heat redistribution on hot Jupiters. *Astrophys. J.* **776**, 134–150 (2013).
16. Stevenson, D. Turbulent thermal convection in the presence of rotation and a magnetic field — a heuristic theory. *Geophys. Astrophys. Fluid Dyn.** 12**, 139–169 (1979).
17. Vidotto, A., Jardine, M. & Helling, C. Early UV ingress in WASP-12b: measuring planetary magnetic fields. *Astrophys. J. Lett.* **722**, 168–172 (2010).
18. Barman, T. S., Hauschildt, P. H. & Allard, F. Phase-dependent properties of extrasolar planet atmospheres. *Astrophys. J.* **632**, 1132–1139 (2005).
19. Agol, E. et al. The climate of HD 189733b from fourteen transits and eclipses measured by Spitzer. *Astrophys. J.* **721**, 1861–1877 (2010).
20. Kislyakova, K. G., Holmstrom, M., Lammer, H., Odert, P. & Khodachenko, M. L. Magnetic moment and plasma environment of HD 209458b as determined from Lyα observations. *Science* **346**, 981–983 (2014).
21. Gough, D. O. The anelastic approximation for thermal convection. *J. Atmos. Sci.* **26**, 448–456 (1969).
22. Rogers, T. M. & Glatzmaier, G. A. Penetrative convection within the anelastic approximation. *Astrophys. J.* **620**, 432–445 (2005).
23. Rauscher, E. & Menou, K. Three-dimensional atmospheric circulation models of HD 189733 b and HD209458 b with consistent magnetic drag and ohmic dissipation. *Astrophys. J.* **764**, 103–121 (2013).
24. Lodders, K. in *Principles and Perspectives in Cosmochemistry* (eds Goswani, A. & Reddy, B. E.) 379–417 (Springer, 2010).
25. Iro, N., Bézard, B. & Guillot, T. A time-dependent radiative model of HD 209458b. *Astron. Astrophys.* **436**, 719–727 (2005).
26. Rogers, T. M. & Showman, A. P. Magnetohydrodynamic simulations of the atmosphere of HD 209458b. *Astrophys. J. Lett.* **782**, L4–L10 (2014).

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Additional information

Supplementary information is available for this paper.

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The author declares no competing financial interests.