Kepler Observations of HAT-P-7: Planet-Induced Gravity Darkening?

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Published in ApJL: Morris, B. M., Mandell, A. M., & Deming, D. 2013, ApJ, 764, L22

Abstract

HAT-P-7b is a hot Jupiter with mass 1.7 M_J orbiting an F6 star with an orbital semi-major axis only four times greater than the radius of its host star. The HAT-P-7 light curve features Doppler, phase and ellipsoidal variations caused by the gravitational perturbation of the shape of the star by the close-orbiting planet. The *Kepler* Space Telescope recorded photometry from May 2009 to June 2011 (Quarters 1-9), spanning 355 orbital phases. **We find a ~10 ppm perturbation to the average transit light curve that we attribute to a temperature decrease on the surface of the star, phased to the orbit of the planet. This cooler spot is consistent with planet-induced gravity darkening, slightly lagging the sub-planet position due to the finite response time of the stellar atmosphere.** The brightness temperature of HAT-P-7b in the Kepler bandpass is T_B = 2733 ± 21 K and the amplitude of the deviation in stellar surface temperature due to gravity darkening is approximately –0.18 K.

Analysis: Primary Transit

- Fit each transit individually to find mid-transit times and generate precise ephemerides
- Phase-fold to create a composite light curve, fit theoretical model by Mandel & Agol (2002) to composite light curve using Levenburg-Marquardt least-squares (see Fig. 1)
- No evidence for significant transit timing variations

Analysis: Gravity Darkening

- The anomaly is not consistent with typical magnetically-driven star spots
- One possible explanation is planet-induced gravity darkening:
  - The tidal distortion of the star due to the planet causes a decrease in the surface gravity near the sub-planet region
  - There is a corresponding decrease in stellar surface temperature and brightness near the sub-planet region
  - "Few 0.1 K" change predicted by Jackson et al. (2012)
- **Here, we construct a simple model to characterize the plausibility of planet-induced gravity darkening as an explanation for the anomaly in the residuals**

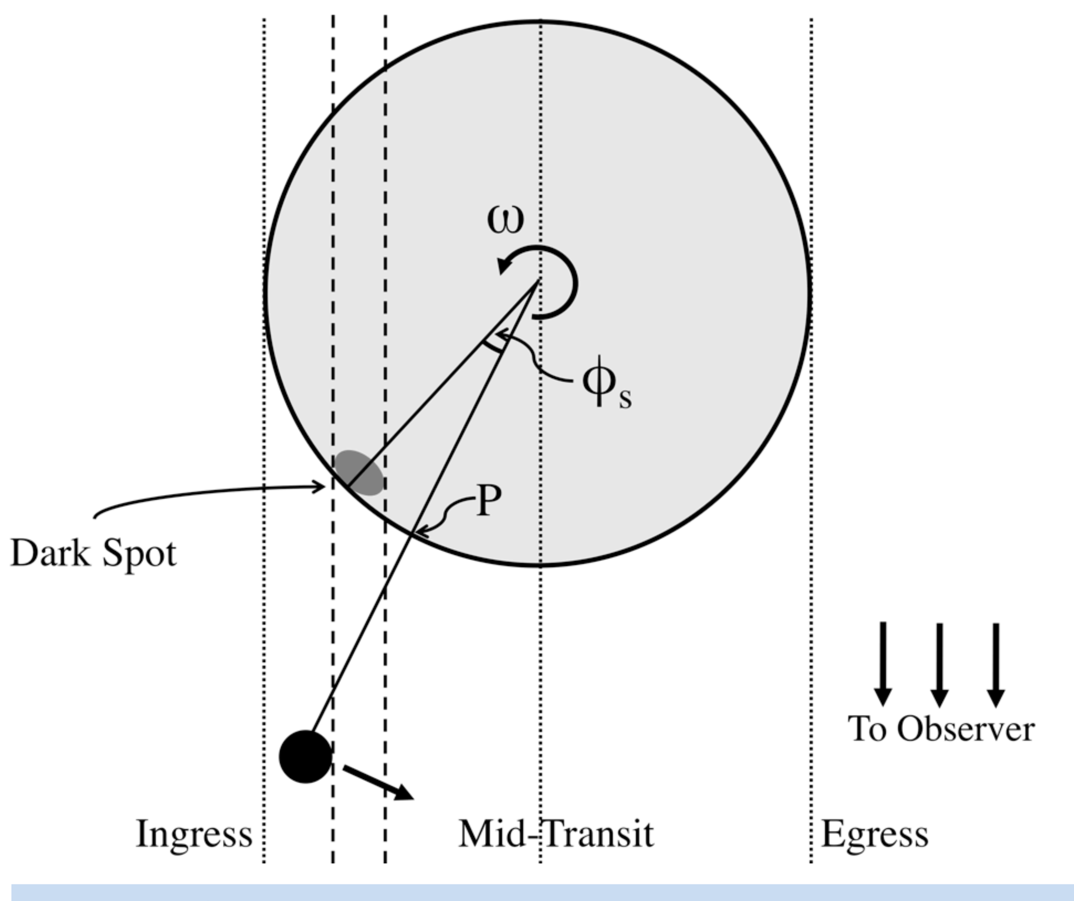

Figure 2 (System geometry): The system geometry is depicted above (not to scale), with the planet represented by the small dark circle, and the star represented by the large grey circle, with a gravity-darkened spot on its surface. The diagram depicts the beginning of the transit across the dark spot, viewed at an angle such that the orbital plane is in the plane of the page.

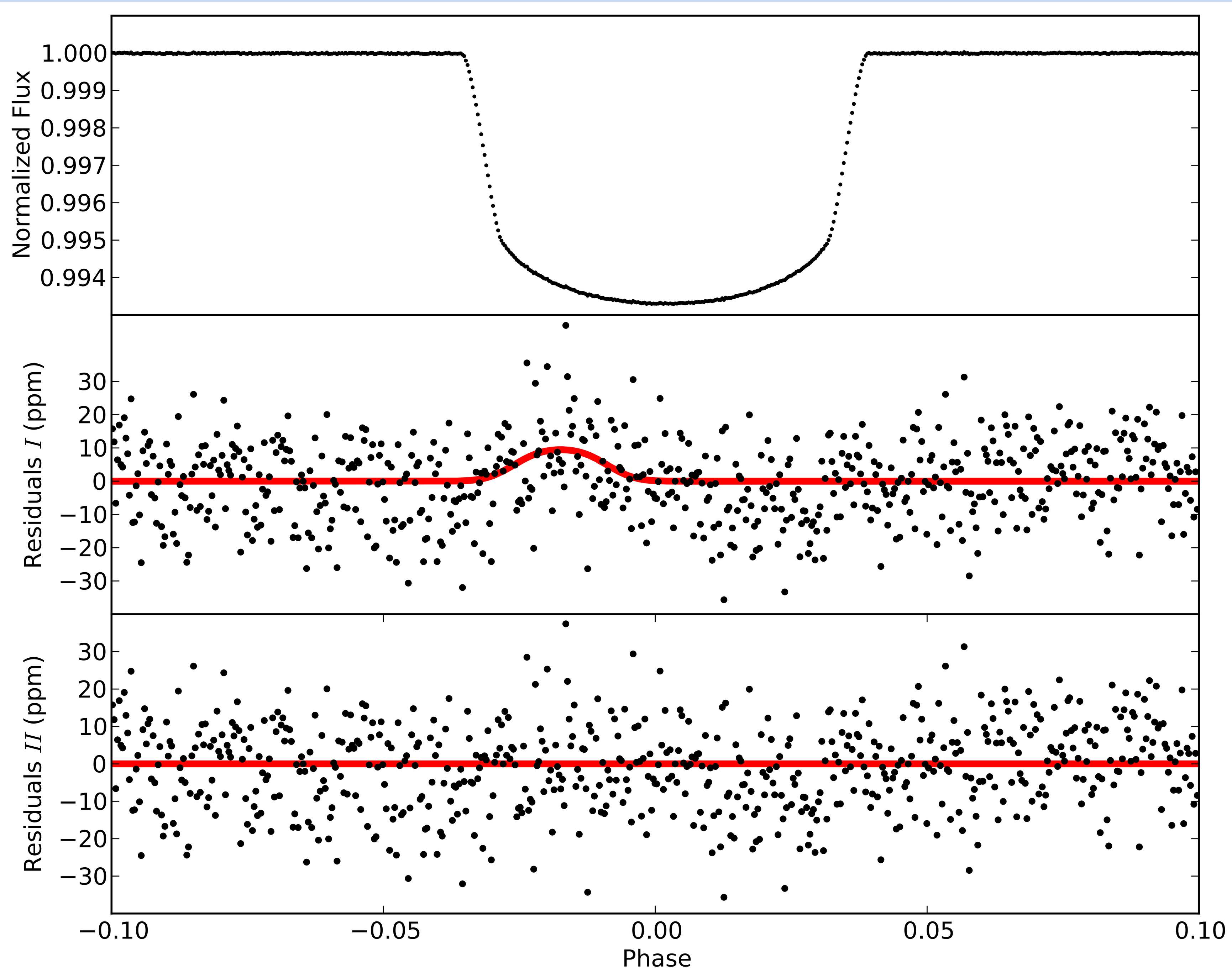

Figure 1 (Transit light curve and anomaly): *Upper*: Composite transit light curve of HAT-P-7b from 326 transits, averaged in one-minute (334 photometric measurement) bins. *Middle*: Residuals after removing the best-fit Mandel & Agol (2002) light curve model. The curve is a simple model for a transit over a planet-induced gravity darkened spot. *Lower*: Residuals after removing the minimum-χ^2 gravity-darkened spot model.

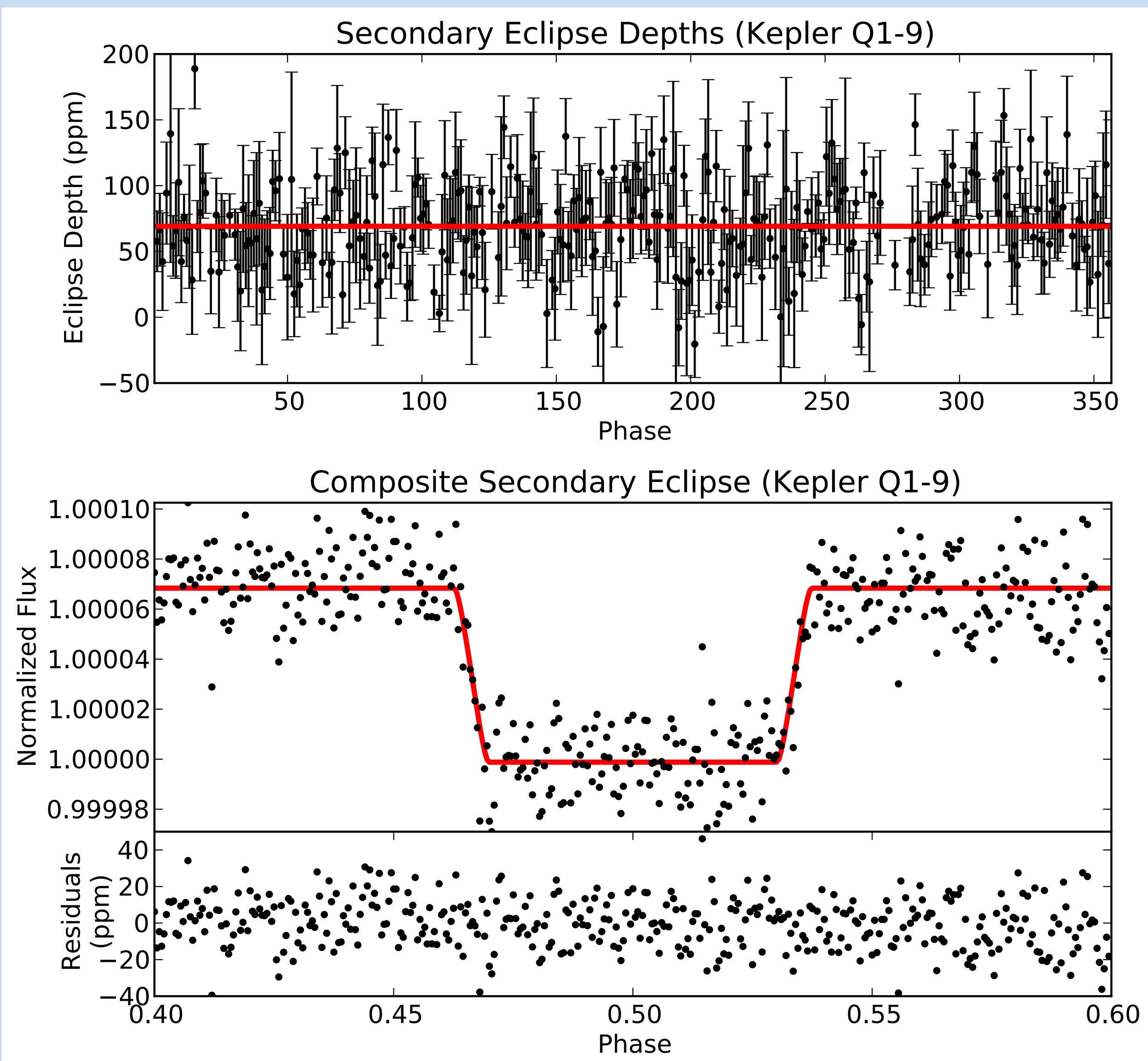

Figure 3 (Secondary Eclipse): *Upper*: Eclipse depth measurements for each orbital phase analyzed, with best-fit depth = 69.1 ± 3.8 ppm (horizontal line). *Lower*: Phase-folded eclipse light curve with best-fit model and residuals for Kepler Quarters 1-9. The photometric measurements are averaged in ~1.5 minute bins (black circles). Error-bars are omitted for clarity.

HAT-P-7 System Parameters

Parameter	Definition	*Kepler* Photometry
P (days)	Period	2.204737 ± 0.000017
T_C (BJD TDB)	Epoch	2454954.357463 ± 0.000005
i (deg)	Inclination	83.111 ± 0.030
R_P/R_*	Ratio of planet to stellar radius	0.07759 ± 0.00003
γ_1	Limb-darkening, linear	0.3525 ± 0.0066
γ_2	Limb-darkening, quadratic	0.168 ± 0.010
a/R_*	Ratio of semi-major axis to stellar radius	4.1502 ± 0.0039
D (ppm)	Secondary eclipse depth	69.1 ± 3.8
T_B (K)	Brightness temperature of planet	2733 ± 21
	Phase at mid-eclipse	0.500051 ± 0.000006

Table 1: Ephemerides (i.e., P and T_c) derived from Levenburg-Marquardt least-squares fits to each transit, and orbital parameters derived by the Levenberg-Marquardt least-squares fit to the composite transit light curve with one-minute binning. The uncertainties of the parameters were calculated using the prayer-bead method. The linear and quadratic limb-darkening coefficients (γ_1 and γ_2) are defined as in the Mandel & Agol (2002) formalism.

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Planet-Induced Gravity-Darkened Spot Model

- The dark spot is assumed to follow a Gaussian intensity profile. Its centroid is located in the orbital plane of the planet and is displaced from the sub-planet point on the stellar surface by some phase lag, ϕ_s (see Fig. 2)
- We calculate the brightness of the system as the planet transits and the dark spot traverses the surface of the star
- We calculate the amplitude, phase lag and width of the anomaly in the transit light curve residuals after removal of the Mandel & Agol (2002) light curve

Dark Spot Model Best-fit Parameters:

- Phase-lag, ϕ_s = 0.056 [phase units]
- Dark spot amplitude, A_s = –106 ppm
- Radial spread of spot, σ_s = 0.037 [phase units]
- The difference of the stellar surface temperature from the temperature of the spot $\boldsymbol{T_{spot} - T_*}$ **= –0.183 K**

Analysis: Secondary Eclipse

- We masked the eclipse and fit to model phase curves to account for the significant phase variation effects, Doppler beaming, planetary reflection
- We fit a Mandel & Agol (2002) model eclipse light curve to each eclipse individually (see Fig. 3)
- Mean eclipse depth D = 69.1 ± 3.8 ppm
- **We find a geometric albedo of < 0.03**, consistent with other observational and theoretical predictions for hot Jupiters (see Barclay et al. 2012, Christiansen et al. 2010)
- If we assume that all of the flux from the atmosphere of the planet is thermal emission, **we find the brightness temperature T_B = 2733 ± 21 K**

Discussion

- The phase-lag of the gravity-darkened spot, Δt, can be computed analytically from first-principles by

$$\Delta t \sim \sqrt{\frac{3k_BT}{5\mu m_H g^2}} \quad (1)$$

- The temperature (T) and surface gravity (g) at the photosphere, where the dark spot manifests, can be inferred from simulations of stellar atmospheres
- Using such models by Kurucz[1], **our observed response time measured by the phase lag of the dark spot, 1.06 × 10⁴ s, is consistent with the Eq. 1 prediction (Δt ~ 1.02 × 10⁴ s)**
- This supports our hypothesis that the perturbation seen in the transit light curve is due to the time-dependent gravity-darkened response of the stellar atmosphere to the passage of the planet
- The detection of the spot is not statistically unequivocal due its small amplitude, though additional Kepler observations should be able to verify the astrophysical nature of the anomaly

References
Barclay, T., Huber, D., Rowe, J. F., et al. 2012, ApJ, 761, 53
Christiansen, J. L., Ballard, S., Charbonneau, D., et al. 2010, ApJ, 710, 97
Jackson, B. K., Lewis, N. K., Barnes, J. W., et al. 2012, ApJ, 751, 112
Mandel, K., & Agol, E. 2002, ApJ, 580, L171
Pal, A., Bakos, G. Á., Torres, G., et al. 2008, ApJ, 680, 1450

[1] Models by Kurucz available on his website: http://kurucz.harvard.edu/grids.html