A Direct Observation of Rapid Heating of an Extrasolar Planet

Gregory Laughlin[1], Drake Deming[2], Jonathan Langton[1], Daniel Kasen[1], Steve Vogt[1], Paul Butler[3], Eugenio Rivera[1], & Stefano Meschiari[1]

[1]*UCO/Lick Observatory, University of California, Santa Cruz, Santa Cruz, CA 95064, USA*

[2]*NASA/Goddard Space Flight Center, Planetary Systems Branch, Code 693, Greenbelt, MD 20771, USA*

[3]*Carnegie Institute of Washington, Department of Terrestrial Magnetism, 5241 Broad Branch Road, NW, Washington, DC 20015, USA*

To date, the Spitzer Space telescope has made near-infrared observations of more than a dozen "Hot Jupiter" extrasolar planets.[1–5] These planets display wide diversity, yet are all believed to have had their spin periods tidally spin-synchronized to their parent stars, resulting in permanent star-facing hemispheres and surface flow patterns that are likely in equilibrium. Planets on significantly eccentric orbits can enable direct measurements of global heating that are largely independent of the details of the hydrodynamic flow.[6] Here, we report 8μm photometric observations of the planet HD 80606b during a 30-hour interval bracketing the periastron passage of its extremely eccentric 111.4 d orbit. As the planet received its strongest irradiation (828 times larger than the flux received at apoastron) its maximum 8μm brightness temperature increased from $\sim$800 K to $\sim$1500 K over a 6 hour period. We also detected a secondary eclipse for the planet, which implies an orbital inclination of $i \sim 90^{\circ}$, fixes

the planetary mass to $M = 4M_{\rm Jup}$, and constrains the planet's tidal luminosity. Our measurement of the global heating rate indicates that the radiative time constant at the planet's 8μm photosphere is approximately 4.5 hours, as compared to 3-5 days in Earth's stratosphere.[7]

The giant planet orbiting the solar type star HD 80606 is unique among the nearly three hundred extrasolar planets that have been found to date.[8] Over a 3-month time scale, it shuttles between the inner edge of its parent star's habitable zone and the highly irradiated close-in realm of the so-called hot Jupiters. Its extremely eccentric orbit provides compelling fossil evidence of a peculiar dynamical history[9], and the planet itself can be used as a laboratory to study the atmospheric dynamics of extrasolar planets. Clues to the planetary interior structure can be gained by measuring the amount of tidal heating experienced by the planet. If its tidal quality factor is of order $Q \sim 3 \times 10^5$ (consistent with that observed for Jupiter)[10,11] then tidal and stellar contributions to the planetary heating should be roughly equal, yielding an orbit-averaged effective temperature $T_{\rm int} \sim 700$ K[9].

The solar-type parent star HD 80606 (with $M_\star \sim M_\odot$, $R_\star \sim R_\odot$ and $T_{\rm eff} = 5800\,{\rm K}$)[8] has a binary companion, HD 80607, lying 17$''$ to the east. Given the 58 pc distance to the system, this implies a projected separation $d \sim 1000$ AU, and the two stars have nearly equal mass and luminosity. We monitored HD 80606 and HD 80607 continuously over a 29.75 hour period using the 8 μm channel of the Spitzer Space Telescope's[12] InfraRed Array Camera (IRAC)[13]. We observed in stellar mode with a cadence of $\sim$14 s. Our observational campaign was timed to start ~ 20 hours before periastron. The geometry of the encounter is shown in Figure 1. Prior to the observations, the planet's orbital inclination was unknown, with the orbital geometry and stellar size indicating a $\sim 15\%$ chance of occurrence of a secondary eclipse centered on the epoch of superior conjunction ($\sim$3 hr prior to periastron). Spitzer collected 8051 256×256 pixel images during the observational campaign.

At periastron, HD 80606b responds to the dramatic increase in insolation by absorbing a fraction of the incident stellar radiative flux. A portion of this absorbed radiation is then re-radiated at 8 μm in a time-varying manner. The rate of this emission depends on the detailed thermal, chemical and radiative properties of the atmosphere. At present, existing near-IR observations of tidally circularized hot Jupiters present an incomplete and somewhat contradictory overall picture. It is not understood, for example, how the wind vectors and temperature distributions on the observed planets behave as a function of pressure depth, and planetary longitude and latitude. Most importantly, the effective radiative time constant in the atmospheres of short-period planets has not been directly measured, and as a result, dynamical calculations of the expected planet-wide flow patterns [14–17] have not come to a full consensus regarding how the surface flow should appear. The lack of agreement between the models stems in part from the paucity of unambiguous measurements of the basic thermal structure of the atmospheres of short-period planets. Hence, photometric near-IR time series of planets such as HD 80606b that are subject to strongly time-dependent heating can provide crucial input data for the next generation of exoplanetary global circulation models.

As expected from earlier experience with IRAC[1,3,4] the data contain a gradually increasing detector sensitivity with time, amounting to several percent over the course of the campaign. This rise (the "ramp") is signal dependent, with strongly illuminated pixels showing a more rapid rise, followed by saturation. Removal of the ramp is complicated by image motion effects arising from tiny drift in the telescope pointing during the long-duration observation. The data contain a net $\sim$0.5 pixel image motion over 30 hours, encompassing both a long-term trend, and a short term (1-hour) oscillation. Image motion affects the shape of the ramp for each pixel because each pixel experiences a different time-dependence of illumination, and because the ramp has a log shape, not linear. We therefore correct for the first order (linear) shifting of photons effect simultaneously with a ramp correction based on a linear plus logarithmic term, as described in detail in the Supplementary Information. The comparison star was analyzed using an identical method. An advantage of the per-pixel ramp removal is that it eliminates need to divide the HD 80606 time series by that of HD 80607, or to normalize to it in any way. Instead, with ramp removal applied to both stars, the HD 80607 time series can be used as an independent control.

The calibrated time series for both HD 80606 and HD 80607 are shown in Figure 2. Whereas the HD 80607 time series shows no significant structure, there are several features of interest in the HD 80606 photometry. Most notably, there is an increase in flux of order $\Delta F/F = 0.001 \pm 0.0002$ during the second half of the time series, which we interpret as arising from an increase in the planet's 8μm emission during the course of the observations.

We model the planetary response during the periastron encounter with a global 2D hydrodynamical model that employs a one-layer, two-frequency radiative transfer scheme[17]. We adopt a 1.1 $R_{\rm Jup}$ planetary radius[18] and an $i = 90^{\circ}$ orbit with the parameters given by the best-fit radial velocity solution, with T_{peri} adjusted to HJD 2454424.86. Given the planet's small periastron distance, it is expected that the planetary spin period will have been pseudo-synchronized[19] to a rate that is similar to the instantaneous orbital angular frequency at periastron. There are several competing theories for the pseudosynchronous frequency.[20] We adopt the following expression[19]

$$\frac{\Omega_{\rm spin}}{\Omega_{\rm orbit}} = \frac{1 + \frac{15}{2}e^2 + \frac{45}{8}e^4 + \frac{5}{16}e^6}{(1 + 3e^2 + \frac{3}{8}e^4)(1 - e^2)^{3/2}}\,,$$

which yields $P_{\rm spin} = 40.7$ h.

Our hydrodynamical model contains three free parameters. The first, $p_{8\mu}$, is the atmospheric pressure at the 8μm photosphere, while the second, X, corresponds to the fraction of the incoming optical flux that is absorbed at or above the 8μm photosphere. The third parameter, p_b, corresponds to the pressure at the base of our modeled layer. We adopt parameter values that allowed our model's light curve to give good agreement with the observed high S/N 8μm time series for HD 189733[4,17]. Specifically, we use $p_{8\mu} = 570$ mbar (adjusted for the higher surface gravity on HD 80606b in comparison to HD 189733b), p_b=4 bars, and X=0.5. Our model photometric light curve is then obtained by integrating at each time step over the planetary hemisphere visible from Earth, and assuming that each patch of the planet radiates a black body spectrum corresponding to the local temperature.

The photometry shows a noticeable dip of duration ~ 0.07 days and amplitude $\Delta F/F = 0.001 \pm 0.0002$ centered near HJD 2454424.74. We identify this feature with a secondary eclipse, as a result of two lines of evidence. First, our fit to the radial velocity data predicts a mid-secondary transit epoch of HJD 2454424.72 ± 0.02, which is consistent with the center of the observed feature. Second, we evaluated the significance of the detection using a bootstrap technique. From the full 8051 frame time series, a sequence of 50,000 bootstrap trials were created based on random scramblings of the deviations from our hydrodynamical model with no transit assumed. For each trial, we adopt a reverse top hat function (of fixed predicted central transit duration of 0.07 d) and fit it to the data by varying the depth and time of center. We record the best-fit depth at each choice of time. For the real unscrambled data, the top-hat fit finds a maximum eclipse amplitude of 0.0015 near HJD 2454424.73. With the planetary and stellar properties given above, and with an $i = 90°$ orbit, the depth of the transit implies an 8μm brightness temperature for the planet of $T_{\rm p}$ ~800 K. The bootstrap trials indicate that this secondary eclipse has been detected with 7 σ confidence.

Having established the occurrence of the secondary eclipse, we can obtain a fit to the eclipse parameters. Using the flux baseline provided by the hydrodynamical model, we construct a grid of eclipse curves having different center times, in-eclipse widths, and ingress/egress times. At each grid point, we fit the eclipse depth and the baseline with a scale factor using linear regression. The three-dimensional space of fitted parameters can be fully sampled, allowing for a direct determination of the minimum χ-square value. Uncertainties are estimated using a standard bootstrap resampling procedure[21]. We find best fit values for the eclipse center time, $T_c =$ HJD 2454424.736 ± 0.003, ingress/egress times, $T_{1,2}$, $T_{3,4} = 0.005 \pm 0.005\,\mathrm{d}$, in-eclipse time $T_{2,3} = 0.070 \pm 0.009\,\mathrm{d}$, and an eclipse depth, $d = 0.00136 \pm 0.00018$.

The secondary eclipse depth and our fit to the photometry indicate that HD 80606b had an effective temperature, $T = 725$ K at the beginning of the photometric observations, which is in accord with the energy output expected for tidal quality factors, $Q \geq 3 \times 10^5$. Our model predicts that the planetary effective temperature on the Earth-facing hemisphere reaches $T_{\rm max} \sim 1250\,{\rm K}$ before starting to turn down near the end of the observational window, and that the effective radiative time constant is estimated as $\tau_{rad} = 4.5 \pm 2\,{\rm hr}$ at the 8μm photosphere. The actual Spitzer 8μm photometry is broadly consistent with this model, although there is little indication of the predicted downturn at the end of the observations. If real, this apparent absence of a flux decrease could signal either rapid advection of heat onto the unilluminated hemisphere, or, alternately, the failure of pseudosynchronization theory to predict $\Omega_{\rm spin}$. The heating rate is consistent with predictions of detailed multi-frequency model calculations of "pL" type cloud-free atmospheres[22], and suggests that the optical albedo of the planet should be low, in agreement with optical full-phase photometry by the MOST satellite for hot Jupiters on tidally circularized orbits.[23]

The depth and duration of the secondary eclipse are consistent with an $i \sim 90°$ orbital inclination for HD 80606b, implying a probability $P \sim 15\%$ that the planet can also be observed in transit. Our radial velocity solution indicates that a central transit (if it occurs) would have a duration of 17 hours, with a midpoint $\sim 6\,{\rm d}$ after the secondary eclipse. Our predicted mid-point ephemerides are $T_{\rm tr} = {\rm HJD}\ 2454653.68 + N \times 111.4277$. The long duration of the transit would allow for precise determination of parameters such as $R_{\rm pl}/R_{\star}$ and i. As a consequence of the planetary deceleration with respect to the star during the transit epoch, the resulting photometric light curve would harbor a detectable asymmetry. Transits would also enable unprecedentedly accurate spectroscopic measurement of the Rossiter-McLaughlin effect[24,25] giving the angle λ, between the stellar rotational axis and the orbital angular momentum vector. If HD 80606 b owes its current configuration to Kozai migration, then one would not expect these two vectors to be aligned.

1. Deming, D., Seager, S., Richardson, L. J., & Harrington, J. Infrared radiation from an extrasolar planet. *Nature* **434**, 740-743 (2005).

2. Charbonneau, D. et al. Detection of thermal emission from an extrasolar planet. *Astrophys. J.* **626**, 523-529 (2005).

3. Deming, D., Harrington, J., Seager, S., & Richardson, L. J. Strong infrared emission from the extrasolar planet HD 189733b. *Astrophys. J.* **644**, 560-564 (2006).

4. Knutson, H. A. et al. A map of the day-night contrast of the extrasolar planet HD 189733b. *Nature* **447**, 183-186 (2007).

5. Grillmair, C.J. et al. A Spitzer Spectrum of the Exoplanet HD 189733b. *Astrophys. J.***658**, L115-L118 (2007).

6. Langton, J. & Laughlin, G. Hydrodynamic Simulations of Unevenly Irradiated Jovian Planets. *Astrophys. J.* **674** 1106-1116 (2007).

7. Salby, M. L. Fundamentals of Atmospheric Physics. San Diego: Academic Press (1996).

8. Naef, D. et. al. HD 80606b, a planet on an extremely elongated orbit. *Astron. Astrophys.* **375**, L27-L30 (2001).

9. Wu, Y., & Murray, N. Planet Migration and Binary Companions: The Case of HD 80606b. *Astrophys. J.* **589**, 605-614 (2003).

10. Goldreich, P., & Soter, S. Q in the solar system. *Icarus* **5**, 375-389 (1965).

11. Peale, S. J. Origin and Evolution of the Natural Satellites *Annual Review of Astronomy and Astrophysics* **37**, 533-602 (1999).

12. Werner, M. W. et al. The Spitzer Space Telescope mission. *Astrophys. J. Suppl.* **154**, 1-9 (2004).

13. Fazio, G. G. et al. The Infrared Array Camera (IRAC) for the Spitzer Space Telescope. *Astrophys. J. Suppl.* **154**, 10-17 (2004).

14. Cho, J. Y.-K., Menou, K., Hansen, B. M. S., & Seager, S. The changing face of the extrasolar giant planet HD 209458b. *Astrophys. J.* **587**, L117-L120 (2003).

15. Burkert, A., Lin, D. N. C., Bodenheimer, P. H., Jones, C. A., & Yorke, H. W. On the surface heating of synchronously spinning short-period Jovian planets. *Astrophys. J.* **618**, 512-523 (2005).

16. Showman, A. P., Cooper, C. S., Fortney, J. J. & Marley, M. S. Atmospheric Circulation of Hot Jupiters: Three-Dimensional Circulation Models of HD 209458b and HD189733b with Simplified Forcing. *Astrophys. J.* In Press (2008).

17. Langton, J., & Laughlin, G. A New Atmospheric Model for HD 189733b *Astrophys. J.* Submitted (2008).

18. Bodenheimer, P., Laughlin, G., & Lin, D. On the radii of extrasolar giant planets. *Astrophys. J.* **592**, 555-563 (2003).

19. Hut, P. Tidal evolution in close binary systems. *Astron. Astrophs.* **99**, 126-140 (1981).

20. Ivanov, P. B., & Papaloizou, J. C. B. Dynamic tides in rotating objects: orbital circularization of extrasolar planets for realistic planet models. *Mon. Not. R. Astron. Soc* **376**, 682-704 (2007).

21. Press, W. H. Teukolsky, S. A., Vetterling, W. T. & Flannery, B. P. Numerical recipes in FORTRAN. The art of scientific computing. Cambridge: University Press, 2nd Ed. (1992).

22. 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).

23. Rowe, J. F. et al. The Very Low Albedo of an Extrasolar Planet: MOST Spacebased Photometry of HD 209458 *Astrophys. J.* Submitted (arXiv:0711.4111) (2007).

24. Queloz, D. et al. Detection of a spectroscopic transit by the planet orbiting the star HD 209458. *Astron. Astrophys.* **359**, L13-L17 (2000).

25. Winn, J. et al. Measurement of Spin-Orbit Alignment in an Extrasolar Planetary System. *Astrophys. J.* **631**, 1215-1226 (2000).

26. Butler, R. P. et al. A Catalog of Nearby Exoplanets. *Astrophys. J.* **646**, 505-522 (2006).

Acknowledgements We thank P. Bodenheimer, D. Charbonneau, J. Fortney, N. Iro, and H. Knutson for useful discussions. This work is based on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. Support for this work was provided by NASA through an award issued by JPL/Caltech.

Competing Interests The authors declare that they have no competing financial interests.

Correspondence Requests for materials should be addressed to G.L. (email: laughlin@ucolick.org).

Figure 1 Orbital geometry of the HD 80606b system. The small dots show the position of the planet in its orbit at one hour intervals relative to the predicted periastron passage at HJD 2454424.84. The size of the parent star HD 80606 is drawn in correct relative scale to the orbit. The position of the planet at times HJD 2454424.2 (labeled 1), 2454424.4 (labeled 2), 2454424.6 (labeled 3), 2454424.8 (labeled 4), 2454425.0 (labeled 5), and 2454425.2 (labeled 6) is shown, with the illuminated hemisphere indicated in each case. HD 80606b induces stellar reflex velocity variations of more than $900\ \mathrm{m\,s^{-1}}$, and the stellar velocity can be measured to $1.5-2.5\ \mathrm{m\,s^{-1}}$ precision[25]. This high RV signal-to-noise allows its orbital parameters to be accurately determined, despite the relatively long orbital period. Using the Keck I telescope, we have extended our data set for HD 80606b to 62 Doppler velocities (tabulated in the Supplemental Information), which, when combined with previously published data[7] give an orbital period $P = 111.4277 \pm 0.0032$ d, an eccentricity, $e = 0.9327 \pm 0023$, a longitude of periastron, $\varpi = 300.4977 \pm 0.0045$, and a radial velocity half-amplitude $K = 471 \pm 5\ \mathrm{m\,s^{-1}}$. The accuracy to which the orbital elements can be determined enabled the scheduling of the Spitzer telescope to observe the star-planet system in the infrared during the periastron passage of Nov. 20, 2007. The pseudo-synchronous rotation rate of the planet is indicated by the successive positions of the small black bar (located at the longitude containing the substellar point at periastron). The temperature distribution on the planet (as predicted by our hydrodynamical model, and as seen by an observer looking down the y-axis) at times 1-6) is shown in the inset diagram. The temperature scale runs from 750K to 1800K.

Figure 2 The light curve of a planet undergoing a close approach to a star. Infrared photometric time series data for HD 80606 (top) and HD 80607 (bottom) for the Spitzer 8 μm observations described in the text. The labels 1-6 correspond to the orbital positions indicated in Figure 1. Our model light curve for HD 80606b is shown in blue, and the predicted midpoint for the secondary transit (from the fit to the radial velocities) is indicated in green. The model assumes $i = 90°$. The depth and duration of the eclipse are determined by our estimates of the planetary and stellar size. The error bars on the photometric data are s.d., as described in detail in the supplemental information.