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LETTER TO THE EDITOR

HD 17156b: A Transiting Planet with a 21.2 Day Period and an Eccentric Orbit

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ABSTRACT

We report the detection of transits by the $3.1 M_{\rm Jup}$ companion to the V=8.17 G0V star HD 17156. The transit was observed by three independant observers on Sept. 9/10, 2007 (two in central Italy and one in the Canary Islands), who obtained detections at confidence levels of 3.0 σ, 5.3 σ, and 7.9 σ, respectively. The observations were carried out under the auspices of the Transitsearch.org network, which organizes follow-up photometric transit searches of known planet-bearing stars during the time intervals when transits are expected to possibly occur. Analyses of the 7.9 σ data set indicates a transit depth $d = 0.0062 \pm 0.0004$, and a transit duration $t = 186 \pm 5$ min. These values are consistent with the transit of a Jupiter-sized planet with an impact parameter $b = a \cos i / R_\star \sim 0.8$. This planet occupies a unique regime among known transiting extrasolar planets, both as a result of its large orbital eccentricity ($e = 0.67$) and long orbital period ($P = 21.2$d). The planet receives a 26-fold variation in insolation during the course of its orbit, which will make it a useful object for characterization of exoplanetary atmospheric dynamics.

Key words. binaries: eclipsing – planetary systems – stars: individual (HD 17156) – techniques: photometric

1. Introduction

During the past several years, the discovery rate of transiting planets has begun to increase rapidly, and twenty transiting planets with secure characterizations are currently known [1]. This aggregate consists mostly of short-period hot-Jupiter type planets, with prototypical examples being HD 209458b (Charbonneau et al., 2000; Henry et al., 2000) and HD 189733b (Bouchy et al., 2005). These planets tend to have $M \sim 1 M_{\rm Jup}$, $2{\rm d} < P < 5{\rm d}$, and tidally circularized orbits.

In the past year, two remarkable discoveries have significantly extended the parameter space occupied by known transiting planets. HD 147506b (Bakos et al., 2007) with $M = 8.04\,M_{\rm Jup}$ is by far the most massive planet known to exhibit transits. It also has the longest orbital period (5.63 days) and a startlingly large orbital eccentricity, $e \sim 0.5$. At the other end of the mass scale, Gl 436b (Butler et al., 2004; Gillon et al., 2007) has $M = 0.07 M_{\rm Jup}$, a 2.64 day orbital period, and an eccentricity $e = 0.15 \pm 0.01$ (Deming et al., 2007). These two planets straddle more than a hundred-fold difference in mass, and their significant non-zero eccentricities are also capable of imparting important information.

At present, infrared observations of transiting extrasolar planets by Spitzer present an incomplete and somewhat contradictory overall picture. It is not understood 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 remains unmeasured, and as a result, dynamical calculations of the expected planet-wide flow patterns (Cho et al., 2003; Cooper & Showman, 2005; Burkert et al., 2005; Langton & Laughlin, 2007; Dobbs-Dixon & Lin, 2007) have come to no consensus regarding how the surface flow should appear. This lack of agreement between the models stems in large part from the paucity of unambiguous measurements of the radiative time constant in the atmosphere. What is needed, is a transiting planet with both a long-period orbit and a large orbital eccentricity. If such a planet were known, then one could use Spitzer to obtain infrared time-series photometry of the planet during the periastron passage. The transit guarantees knowledge of both the geometric phase function and the planetary mass. This information would in turn allow a measured rate of increase in flux to inform us of the planet's atmospheric radiative time constant in the observed wavelength regime.

The orbital periods of the known transiting planets are all significantly shorter than 6 days. This bias is due both to the in-

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[1] see: `http://obswww.unige.ch/~pont/TRANSITS.htm`

trinsically lower geometric probability of transit as one moves to longer periods, and also to the fact that ground-based wide-field transit surveys that rely on photometry folding become very significantly incomplete for planets with orbital periods longer than 5 days. If one wants to detect longer-period transiting planets from the ground, a more productive strategy is to monitor known RV-detected planet-bearing stars at the times when the radial velocity solution suggests that transits may occur. This strategy has the further advantage of producing transits around stars that tend to be both bright and well-suited for follow-up observations.

Long-period transiting planets present an ideal observing opportunity for small telescope observers. Seagroves et al. (2003) have demonstrated that a global network of telescopes, all capable of $\sim$ 1% photometry can easily outperform a single large telescope in terms of efficiency of transit recovery. Since inception in 2002, the Transitsearch.org network has conducted follow-up searches on a number of intermediate-period planets (see e.g. Shankland et al. 2006).

The Doppler-based discovery of HD 17156b was recently published by the N2K consortium (Fischer et al., 2007). The planet has $\mathrm{M}\sin i = 3.12\mathrm{M}_{\mathrm{Jup}}$, with $P = 21.22$ days and $e \sim 0.67$. Fischer et al. (2007) report that the V=8.17 G0V host star has $M = 1.2M_{\odot}$ and $R = 1.47R_{\odot}$. The planet's semi-major axis $a = 0.15$AU thus indicates a periastron distance of $a_{min} = 0.0495\mathrm{AU} = 7.2R_{\star}$. A best fit to the radial velocities indicates longitude of periastron $\omega = 121 \pm 11^{\circ}$. The orbital orientation is favorable, yielding an a-priori geometric transit probability of $P \sim 13\%$.

In their discovery paper, Fischer et al. (2007) reported 241 individual photometric measurements obtained over a 179 day interval, and with a mean dispersion $\sigma = 0.0024$ mag. No significant rotation-induced periodicity was seen. Together, the observations sampled approximately 25% of the $1-\sigma$ transit window, and no evidence for a transit was observed. After the Fischer et al. (2007) discovery paper was made public, the star was added to the Transitsearch.org candidates list[2] and observers throughout the Northern Hemisphere were repeatedly encouraged to obtain photometry of the star[3]. The first available window of opportunity occurred on 9/10 Sept., 2007, with the transit midpoint predicted to occur at HJD 2454353.65 ± 0.30.

2. Observations

We collected data from different observatories during the night of September 9/10, 2007. The following instrumentation was used:

- *Almenara:* Observations were gathered in R band and 7 seconds of exposure time with the TELAST 0.30 m telescope, a stellar photometer devoted to IAC Asteroseismology programs. The telescope is a *f*/10 Schmidt-Cassegrain catadioptric, an SBIG STL-1001E CCD camera provides a field of view of $29' \times 29'$ (scale $1.7''$/px). The night was windy, affecting the telescope (totally exposed), the stars are doubled and even tripled due to this. The gap in the center of the observations was caused by the lost of the guide star due to the wind.
- *Bissinger:* Observations were made from Pleasanton, California USA using a 0.4 m diameter modified Schmidt-Cassegrain telescope operating at *f*/6 with an SBIG ST-10XME CCD camera and a Bessell I band filter. Imaging began at 04:05 UT on 10 Sept. and ended at 09:09 UT on 10 Sept. with an exposure cadence of 43 seconds. Bins of 15 exposures were made producing a flat light curve with an r.m.s. of 0.003 mag.
- *Gasparri:* The telescope used is a commercial 0.25 m *f*/4.8 Newtonian, located near Perugia, Italy. The camera is a SBIG ST-7XME with KAF-0402 CCD providing a field of view of $19.8' \times 13.2'$ with sampling of $1.55''$/px. The photometric observation started at 20 UT on 9 Sept. and stopped at 04 UT on Sept. 10. The presence of some clouds and veils limit the useful data to 00-02 UT of 10 Sept. Exposures were made through a near-IR filter, and are of 20s duration, with 339 useful images were collected.
- *Lopresti:* Observations were conducted at La Spezia, Italy with a Maksutov–Newton telescope of 0.18 m diameter *f*/4 and an SBIG ST-10xme CCD camera, with a framed field of $70' \times 47'$ (scale $1.7''$/px). Observations run from 20 UT 9 Sept. through 04 UT 10 Sept. Exposure times are 5s. A total of 580 R band images were collected.
- *Manzini:* The Stazione Astronomica di Sozzago is an observatory located in Sozzago (Novara) Italy (international code IAU A12). Observations were conducted with a 0.40 m Cassegrain telescope *f*/6.7, equipped with a CCD camera Hi-SIS43ME (FoV $18' \times 11'$, scale $0.7''$/px). Useful data were collected until 20 UT 9 September, when clouds intervened.

3. Data Analysis

All the raw images were calibrated in the standard way; each observer took a series of images to correct for the irregular pixel sensivity (flat-fielding) and dark current effects. Out of the 6 datasets, only three cover the central transit window. These were obtained by the amateur astronomers Lopresti and Gasparri (in Italy), and by Almenara (at the IAC). Unfortunately, the data are irregular in their coverage of the transit and in their precision.

The three data sets were analyzed with IDL routines to perform simple aperture photometry. The center of the aperture was calculated by a gaussian fit, and the aperture was held fixed (to 15-20 px in radius, depending on the data set). We removed the sky background contribution after an estimation of its value in an annulus around the target aperture. The brightest stars in the field were measured the same way, and a reference light curve was constructed by adding the flux of these stars. The target flux was divided by this reference to get the final normalized curve. The data included in this detailed analysis are:

- Almenara (A): From 6 hours before center to 3.4 hours after transit center. The dispersion is high at the beginning, and better at the end, decreasing from 0.5% to 0.4% (in a k-sigma filtered version of the original light curve). Two stars were used to build the reference light curve.
- Gasparri (G): From 2 hours before center to 1.1 hours after center. Three stars were used to build the reference star. The r.m.s. of the residuals is ~0.4%. Soon before transit center there is a rise in the light curve that we were not able to correct, due to the clouds and veils affecting differently the target and each of the stars used to build the reference.
- Lopresti (L): From 4 hours before transit center to 1.5 hours after transit center. The last 45 minutes were taken with a 180° rotation of the CCD (due to the mount configuration). We have not been able to fully correct for the effect of this rotation, as data are sensitive to uncorrected minor flat field effects. To avoid the introduction of offsets, we have thus

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[2] http://207.111.201.70/transitsearch/dynamiccontent/candidates.html

[3] see www.oklo.org

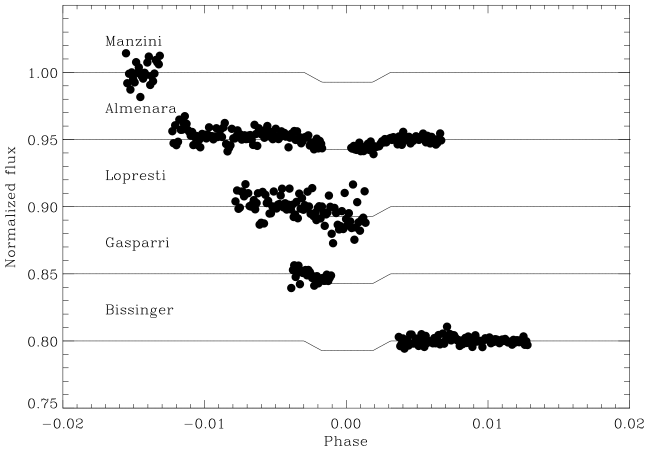

Fig. 1. Normalized light curves of HD 17156 at the moment of transit, and the best fitted trapezoid to the Almenara data set (solid lines). Data sets of different observers have been shifted each other by 0.05 for clarity. The transit is centered in HJD 2454353.61

ignored these last data. Three stars were used to build the reference light curve. The r.m.s. of the residuals is ~0.9%.

The final data sets are plotted in the Fig.1. We performed a fit to a trapezoidal function, with four free parameters: center, width, depth and size of the transition between the two levels of the trapezoid. The significance of the transit detection was then evaluated as the value of the depth of the trapezoid divided by the dispersion of the fit. Thus, we obtain a 5.6 σ detection for the (A) set. This value increases to 7.9 σ once the baseline is corrected by a parabolic fit to the parts of the light curve outside of the trapezoid, plus an extra margin of 0.001 in phase to avoid the inclusion of points inside transit. For the (L) and (G) data sets the free parameters for the trapezoid fitting were only the depth and center. The other two parameters were set to the result of the fit in the (A) set. We obtain the values of 5.3 σ and 2.97 σ, respectively.

Due to the quality of the three data sets, we believe it is too dangerous to perform a combined analysis; specially the zero offsets are not too clear in the Gasparri (G) and Lopresti (L) data sets, and they might dominate the result of a fitting to a combined light curve. We thus analyzed the most homogeneous and least noisy part of the data, namely the egress recorded in the (A) set, to determine the main characteristics of the transit. We employed two strategies: fitting to a trapezoid to estimate the depth of the transit, and fitting to a model of an eccentric transit, following the formalism of Giménez (2006).

In order to correct for the baseline, the trapezoid fit to the egress was performed in two steps: (1) A first trapezoid is fitted, removed from the light curve, and a line is fitted to the residuals. This line is removed from the original light curve and (2) a second trapezoid is fitted, providing the values of the depth and time of egress. The errors are evaluated by a bootstrap analysis, performing 20 000 tests with data sets in which 50% of the residuals points were randomly re-sorted, and the best fitted model was re-added to the residuals to build the data set. The same two-step fitting was performed in each data set. The depth of the trapezoid was found to be 0.0062±0.0004.

The second strategy consisted in a fit to the equations of Giménez (2006). The fitted parameters were the phase of start of the transit, k, i, and three coefficients defining a parabolic baseline correction. The two non-linear limb darkening coefficients were fixed to $u_+ = 0.65$ and $u_- = -0.05$ (see Giménez (2006) for a definition of these coefficients) from the tables of Claret (2000) for ATLAS stellar models. The eccentricity and the longitude of the periastron were fixed to values obtained from Fischer et al. (2007). The best solution was obtained by minimizing the χ^2 between the model and the observations using the algorithm AMOEBA (Press et al., 1992). The errors were estimated by a bootstrap analysis similar at that described above, performing 1 500 tests. The best fitted values using this technique are reported in Table1.

Table 1. Transit fit and planetary parameters for HD 17156 b

Parameter	Value
T_{mid} (HJD)	2 454,353.61 ± 0.02
ϕ_{egress}	0.003050± 0.000075
Transit duration (day)	0.1294 ± 0.0367
$k = R_p/R_\star$	0.08007 ± 0.0028
i (deg)	87.89 ± 0.10
R_p (R_{Jup})	1.15 ± 0.11

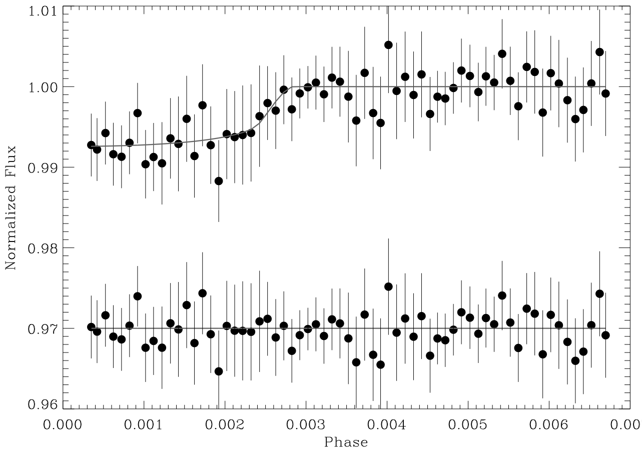

Fig. 2. Top: Normalized phase plot of the egress of the transit of HD 17156 from the (A) data set. The error bar in each point it was calculated as the standard deviation of the 20 points closest to the point i. The plotted error bars are 2 times this quantity. The overplotted line is the best fitted model using the formalism of Gimenez as described in the text. Bottom: the residuals of the fit.

Based on the inclination, the planet mass is then $M_p = 3.12 \pm 0.5 M_{\mathrm{Jup}}$. Based on the radius of the star and the k determination, the radius of the planet is $R_p = 1.15 \pm 0.11 R_{\mathrm{Jup}}$. These properties are summarized in Table1, the final fit and the residuals are plotted in Fig.2.

As additional test we have checked the Hipparcos photometry (Perryman & ESA, 1997). Hipparcos observed HD 17156 (HIP 13192) on 142 occasions with a standard deviation of 0.0013 mag. An inspection of the light curve folded with the orbital period of the planet shows only two photometric points close to the transit window.

During the night of September 30 / October 1, HD 17156b was observed from the Mount Laguna Observatory in southern California. The team composed by William Welsh, Abhijith Rajan, Jonathan Irwin, Philip Nutzman and David Charbonneau kindly report to us (Charbonneau, personal communication) that the transit ingress was observed near Oct 1 UT 6:30, and a flat bottomed event followed, egress was lost due to clouds.

In addition, observer Davies, located in Torrance, California, obtained $\sim 10,000$ CCD images which show clear evidence of a full transit. These data will be analyzed in detail in a forthcoming paper.

4. Discussion

The detection of transits by a planet with a three-week orbital period demonstrates the utility of ad-hoc networks of small telescopes for obtaining photometric follow-up of planets whose orbital parameters have been determined via Doppler radial velocities. Indeed, the transits of HD 17156b offer a plethora of interesting opportunities for follow-up observations.

With its high orbital eccentricity and small periastron distance, HD 17156b appears to bear a curious kinship to HD 80606b, HD 147506b, and HD 108147b. All three of these planets occupy a locus of the a–e plane where they should actively be undergoing tidal dissipation, and therefore they should be generating significant quantities of excess interior heat. Our measurement indicates that tidal heating is not significantly inflating the planetary radius. The nominal $R = 1.1 R_{\rm Jup}$ radius predicted by baseline models (e.g. those of Bodenheimer et al. 2003) is confirmed by our observations.

Follow-up photometric measurements during future transits will allow a more accurate determination of the orbital inclination of HD 17156b. An improved value for i, in turn, will generate an accurate assessment of likelihood that the planet can be observed by Spitzer in secondary transit, and will enable a much-improved constraint on the still-uncertain radius of the parent star. In the event that secondary transits can be observed, a direct measurement of the excess tidally generated luminosity from the planet is a distinct possibility (see e.g. Deming et al. 2007).

As a consequence of its highly eccentric orbit, HD 17156b experiences a 26-fold variation in insolation during the 10.6 day interval between periastron and apoastron. This extreme radiative forcing may drive interesting, and potentially observable dynamical atmospheric flows on the planet (Langton & Laughlin, 2007). The large tidal forces experienced during periastron have almost certainly forced the planet into pseudo-synchronous rotation (e.g. Goldreich & Peale 1968; Hut 1981; Papaloizou & Ivanov 2005). Rotationally induced modulation in the infrared light curve following periastron is potentially observable, and may be of great utility in selecting between the current divergent predictions for the actual value of the pseudo-synchronous spin frequency.

HD 17156b is quite massive, as is often the case for planets orbiting one member of a binary pair (Desidera & Barbieri, 2007), and the eccentricity is large. These characteristics favor a formation scenario involving migration and/or dynamical evolution in the presence of a sufficiently close external perturber. Such a perturber could be either a companion star or an additional planet(s) in the system.

For some of the close-in planets with $m \sin i > 1.5\ M_{\rm Jup}$ orbiting single stars, there are already indications of a history of significant dynamical perturbations. For example, HD 118203b, HD 68988b and HIP 14810b all have anomalously high eccentricities that may be indicative of additional perturbing companions, perhaps with masses below (or periods longer than) the threshold of immediate radial velocity detection (This is certainly the case for HD 68988b and HIP 14810b, which both have long-period planetary companions Butler et al. 2006). Due to mutual perturbations, the eccentricities of the bodies in the precursor system may have grown to the point where crossing orbits were achieved. Repeated close encounters among the planets would have then generated a period of chaotic evolution that typically terminates with the ejection of one planet on a hyperbolic trajectory (Marzari & Weidenschilling, 2002).

Alternately, a stellar companion could also effectively trigger dynamical evolution or instability in a precursor system, eventually leading to the current configuration (for some examples, see Marzari & Barbieri 2007a,b; Wu & Murray 2003). With reference to a stellar companion, a quick inspection of POSSI, POSSII, and 2MASS images do not reveal any clear association between faint field stars and HD 17156. The only potentially interesting source is 2MASS 02494068+7144583. It shows an appreciable proper motion, but in the opposite direction of the proper motion of HD 17156. The star lies 22.2″ from HD 17156; if they are at the same distance, the apparent separation is ~1740 AU.

A combination of continued radial velocity monitoring of HD 17156, in conjunction with accurate measurements of successive transit midpoints, gives hope for the detection and accurate characterization of additional bodies in the system via a novel set of constraints.

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