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STELLAR VARIABILITY OF THE EXOPLANET HOSTING STAR HD 63454

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ABSTRACT

Of the hundreds of exoplanets discovered using the radial velocity (RV) technique, many are orbiting close to their host stars with periods less than 10 days. One of these, HD 63454, is a young active K dwarf which hosts a Jovian planet in a 2.82 day period orbit. The planet has a 14% transit probability and a predicted transit depth of 1.2%. Here we provide a re-analysis of the RV data to produce an accurate transit ephemeris. We further analyze 8 nights of time series data to search for stellar activity both intrinsic to the star and induced by possible interactions of the exoplanet with the stellar magnetospheres. We establish the photometric stability of the star at the 3 mmag level despite strong Ca II emission in the spectrum. Finally, we rule out photometric signatures of both star–planet magnetosphere interactions and planetary transit signatures. From this we are able to place constraints on both the orbital and physical properties of the planet.

Key words: planetary systems – stars: individual (HD 63454) – techniques: photometric – techniques: radial velocities

1. INTRODUCTION

The number of known exoplanets has now well exceeded 500, revealing a large diversity in both planetary properties and orbital characteristics. In the early days of exoplanet discoveries, one of the first surprises was that of very short period planets, the so-called hot Jupiters. Studies have been undertaken which attempt to find star–planet interactions between these hot Jupiters and their host stars, and correlations of stellar activity with planetary emission spectra (Knutson et al. 2010) and surface gravities (Hartman 2010) have been detected. Evidence has also been found for a general increase in chromospheric activity of stars that harbor short-period planets (Canto Martins et al. 2011) and surveys have been undertaken that evaluate such activity in potential planet search targets (Arriagada 2011). Most of these effects are caused by interactions between coronal magnetic fields and the magnetospheres of the close-in planets (Cohen et al. 2009; Lanza 2009). Searches for observable signatures of such interactions have been undertaken for HD 189733 (Fares et al. 2010) and CoRoT-6 (Lanza et al. 2011) but the evidence has been inconclusive. Shkolnik et al. (2008) observed synchronicity of the Ca II H and K emission for both HD 179949 and υ and with the rotation of their respective short-period planets, likely due to interactions with the stellar magnetic fields.

The 2.82 day period planet orbiting HD 63454 (HIP 37284, TYC 9385-1045-1) was first detected by Moutou et al. (2005) using RV data obtained with the High-Accuracy Radial-velocity Planet Searcher (HARPS) mounted on the ESO 3.6 m telescope. The host star is a relatively young (∼1 Gyr) late-type (K4V) star. The activity indicators in the discovery data show that the star is active and they report RV jitter which is attributed to the stellar activity. Since the star is young, it is predicted to have a relatively short rotation period of ∼20 days. This star is extremely southern in declination ($-78°$) and so follow-up observations of the system have been minimal since the planet's discovery.

Here we present the results of photometrically monitoring HD 63454 as part of the Transit Ephemeris Refinement and Monitoring Survey (TERMS; Kane et al. 2009). The star was observed over a 2 week period in order to extract variability properties of the star. In particular, we are interested in variability that may correspond with the RV jitter and/or the influence of the planet on the star. We find no evidence of such correlations, which places limits on the causation of stellar activity due to the interactions of the planet. We present additional HARPS data which refine the period and redetermine the phase of the planet. We subsequently monitored transit windows and confirm that this planet does not transit the host star. With such a small orbital period, we use this result to place a lower limit on the mass of the planet and an upper limit on the radius of the planet.

2. KEPLERIAN ORBIT AND TRANSIT EPHEMERIS

The original discovery of HD 63454b presented by Moutou et al. (2005) included 26 RV measurements acquired using the HARPS instrument and were subject to an additional analysis by Babu et al. (2010). Here we present eight additional measurements from HARPS acquired since then which have been used to refine the orbital parameters and redetermine the phase of this planet. All 34 measurements are shown in Table 1.

The stellar mass according to Moutou et al. (2005) is $M_\star = 0.8\,M_\odot$ and the surface gravity is $\log g = 4.23$. More accurate stellar parameters were measured from HARPS spectra by Sousa et al. (2008), which we have used to refine the stellar mass and radius. They find the effective temperature, surface gravity, and metallicity to be $T_{\mathrm{eff}} = 4840 \pm 66$ K, $\log g = 4.30 \pm 0.16$ cm s^{-2}, and [Fe/H] $= 0.06 \pm 0.03$, respectively. Using the polynomial relations of Torres et al.

Table 1
HARPS Radial Velocities

Date (JD −2440000)	Radial Velocity (km s^{-1})	Uncertainty (km s^{-1})
13047.625113	33.78298	0.00321
13060.629178	33.90876	0.00435
13061.601527	33.79109	0.00308
13063.592466	33.89097	0.00290
13064.637653	33.78317	0.00366
13066.590014	33.87237	0.00271
13145.500240	33.85952	0.00268
13146.479839	33.78204	0.00240
13147.463245	33.89531	0.00551
13151.455026	33.83624	0.00323
13152.452481	33.82294	0.00345
13153.473472	33.91101	0.00199
13156.443421	33.90046	0.00316
13158.466001	33.85960	0.00485
13295.880778	33.78365	0.00177
13314.841071	33.83579	0.00161
13340.808816	33.79013	0.00173
13342.779095	33.85122	0.00232
13344.787166	33.90508	0.00175
13346.788259	33.79824	0.00140
13369.736742	33.86615	0.00142
13371.762067	33.78346	0.00186
13372.728689	33.88211	0.00178
13375.769216	33.89765	0.00194
13377.779025	33.80591	0.00321
13400.742286	33.85003	0.00193
13402.640683	33.77902	0.00309
13403.736539	33.88467	0.00157
13405.746675	33.77627	0.00181
13406.654971	33.89017	0.00164
13408.668892	33.80302	0.00173
13468.516837	33.87624	0.00232
15260.618227	33.83241	0.00095
15262.516387	33.76660	0.00077

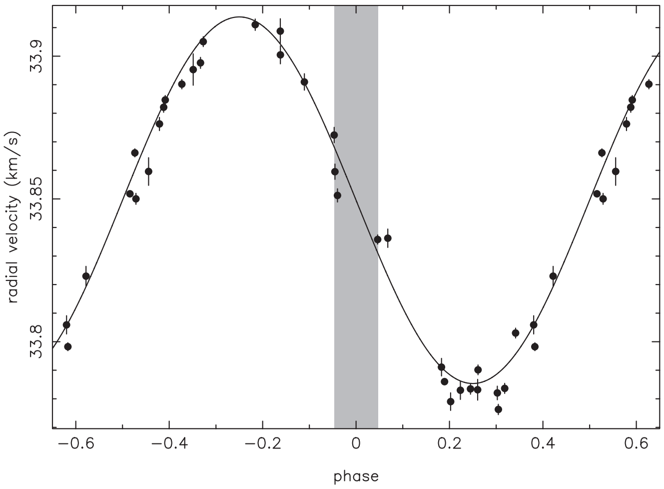

Figure 1. Radial velocity measurements of HD 63454 along with the best-fit orbital solution (solid line). The shaded region shows the extent of the 1σ transit window.

Table 2
Keplerian Fit Parameters

Parameter	Value
P (days)	2.818049 ± 0.000071
T_c [a] (JD −2440000)	15583.240 ± 0.068
T_p [b] (JD −2440000)	13342.870 ± 0.590
e	0.000 ± 0.022
K (m s^{-1})	64.19 ± 1.65
ω (°)	87.3 ± 90.5
dv/dt (m s^{-1} yr^{-1})	-3.95 ± 0.95
χ^2_{red}	10.14
rms (m s^{-1})	6.84

Notes.
[a] Time of transit.
[b] Time of periastron passage.

(2010), we derive revised stellar parameters of $M_\star = 0.84\,M_\odot$ and $R_\star = 1.05\,R_\odot$ for HD 63454.

We fit a single-planet Keplerian solution to the RV data using the techniques described in Howard et al. (2010) and the partially linearized, least-squares fitting procedure described in Wright & Howard (2009). The inclusion of a linear trend to the solution reduced the χ^2_{red} from 30.68 to 10.14 and the rms of the residuals from 10.87 to 6.84 m s^{-1}. While an offset between the bulk of the data and the final two measurements of $\sim$20 m s^{-1} would produce comparable reduction in the χ^2_{red}, HARPS is known to be extremely stable and such an offset is not considered plausible. This led us to favor the solution which includes a trend. Further RV data are required to ascertain the precise source of the trend, whether it be due to the magnetic cycle of the star or the presence of an additional companion within the system. The adopted solution with the trend is shown in Table 2. The parameter uncertainties were determined from the sampling distribution of each parameter through a non-parametric bootstrap analysis (Freedman 1981). The folded data and adopted model with the trend removed are shown in Figure 1.

Using the aforementioned stellar mass, we derive a planetary mass of $M_p \sin i = 0.398\ M_J$ and a semimajor axis of $a = 0.0368$ AU. We estimate the planetary radius using the models of Bodenheimer et al. (2003) to be $R_p = 1.098\ R_J$. This results in a predicted transit probability of 14.3%, a depth of 1.2%, and a transit duration of 0.13 days. A preliminary search by Moutou et al. (2005) found no evidence for transits of this planet. In Figure 1, we include a shaded region which indicates the calculated size of the transit window (Kane et al. 2009) at the time of acquiring our photometry. This is described further in Section 5 where we present re-phased photometry which places limits on transits and the inclination or size of the planet.

3. PHOTOMETRY

3.1. Photometry from *Hipparcos*

We investigated the low-frequency photometric stability of HD 63454 using observations from the *Hipparcos* satellite. *Hipparcos* observed the star during its 3 year mission and acquired a photometric data set consisting of 124 measurements spanning a period of 1180 days (Perryman et al. 1997), shown in Figure 2. The 1σ rms scatter of the 124 HD 63454 measurements is 0.031 mag, while the mean of the measurement uncertainties is 0.019. The scatter is roughly 50% higher than the expected uncertainty of a single observation, but the range, 0.345 mag, is significantly more than that expected from a constant star. Consequently, the *Hipparcos* Catalog described by Perryman et al. (1997) lists the variability type for HD 63454 as a blank, indicating that the star "could not be classified as variable or constant." We performed a Fourier analysis of the *Hipparcos*

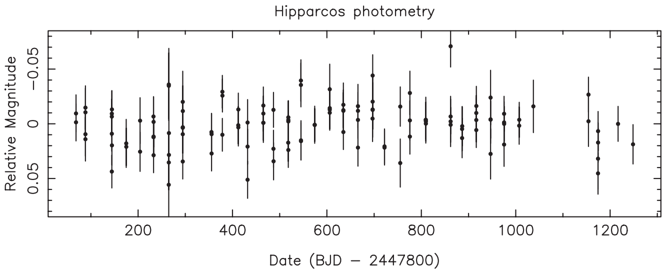

Figure 2. Photometry of HD 63454 from the *Hipparcos* mission.

data and do not detect any significant periodic variability. However, this only rules out activity above the 3% level. Additionally, the Nyquist frequency of the data is 0.0525 days^{-1} which is slightly above the predicted frequency of the stellar rotation, thus resulting in substantial aliasing at smaller periods. The strongest peaks in the periodogram occur at 0.25 and 0.27 days but the power of these peaks is very low.

3.2. *Photometry from CTIO*

Observations of HD 63454 were carried out at the Cerro Tololo Inter-American Observatory (CTIO) 1.0 m telescope using the Y4KCam Detector,[8] which is a 4k×4k CCD with a field of view of about 20 arcmin on the side. The target was observed along with three comparison stars with a Johnson *V*-band filter for 8 nights during the period 2011 January 22–30. An additional night of data was acquired using this telescope on the night of 2011 April 5 in order to complete phase coverage of the transit window (see Section 5). The brightness of the target ($V = 9.37$) led to exposure times of 8–12 s, high enough to eliminate the effects of shutter errors. The principal target and comparison stars were carefully placed on cosmetically clean regions of the CCD and kept in exactly the same place during the monitoring sequences to avoid inter-pixel sensitivities.

The target star HD 63454 is known in the 2MASS catalog as 2MASS J07392187−7816442 (Skrutskie et al. 2006). There is a nearby fainter star 6.14 arcsec away (2MASS J07391989−7816428) for which the *JHK* magnitudes are 10.636, 12.523, and 12.350, respectively. According to the photometric quality flags of the 2MASS catalog, the *J* value represents an upper limit on the magnitude (i.e., represents a minimum brightness for the star). The $H{-}K$ value of 0.173 means the star is an early M star if on the main sequence.

Aperture photometry was performed on each star by extracting small regions from the image, ±100 pixels from the estimated center of the stellar point-spread function (PSF). The size of the photometric aperture was limited to restrict light contamination from the nearby star, which was particularly important during nights of bad seeing which may cause the PSF to spread further into the aperture. To achieve sufficient precision to detect low-amplitude variability including transit signals, we performed relative photometry using the methods described in Everett & Howell (2001). The resulting photometry was binned into equal time intervals of 5 minutes each and are shown in the top panel of Figure 3. For most nights the 1σ rms was less than 3 mmag, but the combined data set has a 1σ rms of 3.4 mmag.

4. PHOTOMETRIC FOURIER ANALYSIS

Here we describe an analysis of the photometry for the purposes of studying the stability of the star. To investigate the high-frequency variability of HD 63454, we used a weighted Lomb–Scargle (L–S) fourier analysis, similar to that described by Kane et al. (2007). In particular, we are interested in activity related to the magnetic cycle and interactions of the magnetic field and chromosphere with the planet on the short timescales of its orbital period. Investigation of the line bisector inverse slope by Moutou et al. (2005) found no correlation with the orbital period. In the bottom-left panel of Figure 3, we show the complete CTIO data set folded on the orbital period from Table 2. Phase zero in this figure is the location of the predicted transit time of the planet.

As described by Dawson & Fabrycky (2010), aliases in periodograms result from discrete sampling times which occur to a lesser degree with unevenly sampled data. The periodogram of the 2011 January photometry is shown in the bottom-right panel of Figure 3. There are significant aliases at periods less than 1 day that are harmonics of the observing schedule, such as 0.20, 0.26, 0.60, and 1.50 days. Of note is the strongest peak located at 0.26 days because this lies between the two strongest peaks located in the *Hipparcos* data (see Section 3.1). This is assumed to be the result of the cadence and resulting Nyquist frequency in each data set, but we note it here as a possible indicator of low-amplitude high-frequency activity. Observations of each night lasted ∼0.3 days which results in broadening of the peaks in the spectral window function and a double peak at 0.35 and 0.37 days. The strongest feature in the periodogram beyond a period of 1.5 days is a peak located at 2.90 days. Although tantalizingly close to the measured orbital period of 2.82 days, the broadness of the peak and strength of the signal are inconclusive as to a planetary origin, particularly when it is equally close to an expected alias at 3.00 days. By way of contrast, the magnetic activity in CoRoT-6 exhibits a photometric variation with a period of 6.4 days and an amplitude of 2.7% (Lanza et al. 2011). We thus conclude that the star is stable at the 3 mmag level over both stellar rotation and planetary orbital timescales.

For short-period planets, the orbit may be inside the magnetic field of the host star in which case an electric field is generated by the interaction of the stellar and planetary magnetic fields (Jardine & Collier Cameron 2008). The planet orbiting HD 63454 is at a separation of 7.5 $R_\star$ which, for the relatively young K dwarf (∼1 Gyr), may place it inside the stellar magnetosphere given the expected rotation period. Thus, an additional test would be to attempt the detection of a time variable radio flux emission from the star–planet interaction as was performed for HD 189733b by Fares et al. (2010).

5. PLANETARY TRANSIT EXCLUSION

Moutou et al. (2005) state that their photometry "showed no planetary transit" although they do not present the photometry or the precision of the measurements. Here, we present our photometry acquired during transit windows based upon the revised orbital parameters and ephemeris and discuss limits on the implied properties of the planet and orbital inclination. To demonstrate the importance of refining orbital parameters, the observations during the January CTIO run were designed to cover two transit windows based upon the orbital parameters of Moutou et al. (2005). However, the orbital fit to the updated HARPS data shifted the predicted windows into the observing gaps in orbital phase, thus necessitating the additional night of data in April.

Figure 4 shows a zoomed-in version of the lower-left panel of Figure 3, where the data once again has been phased on a zero

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[8] http://www.astronomy.ohio-state.edu/Y4KCam/

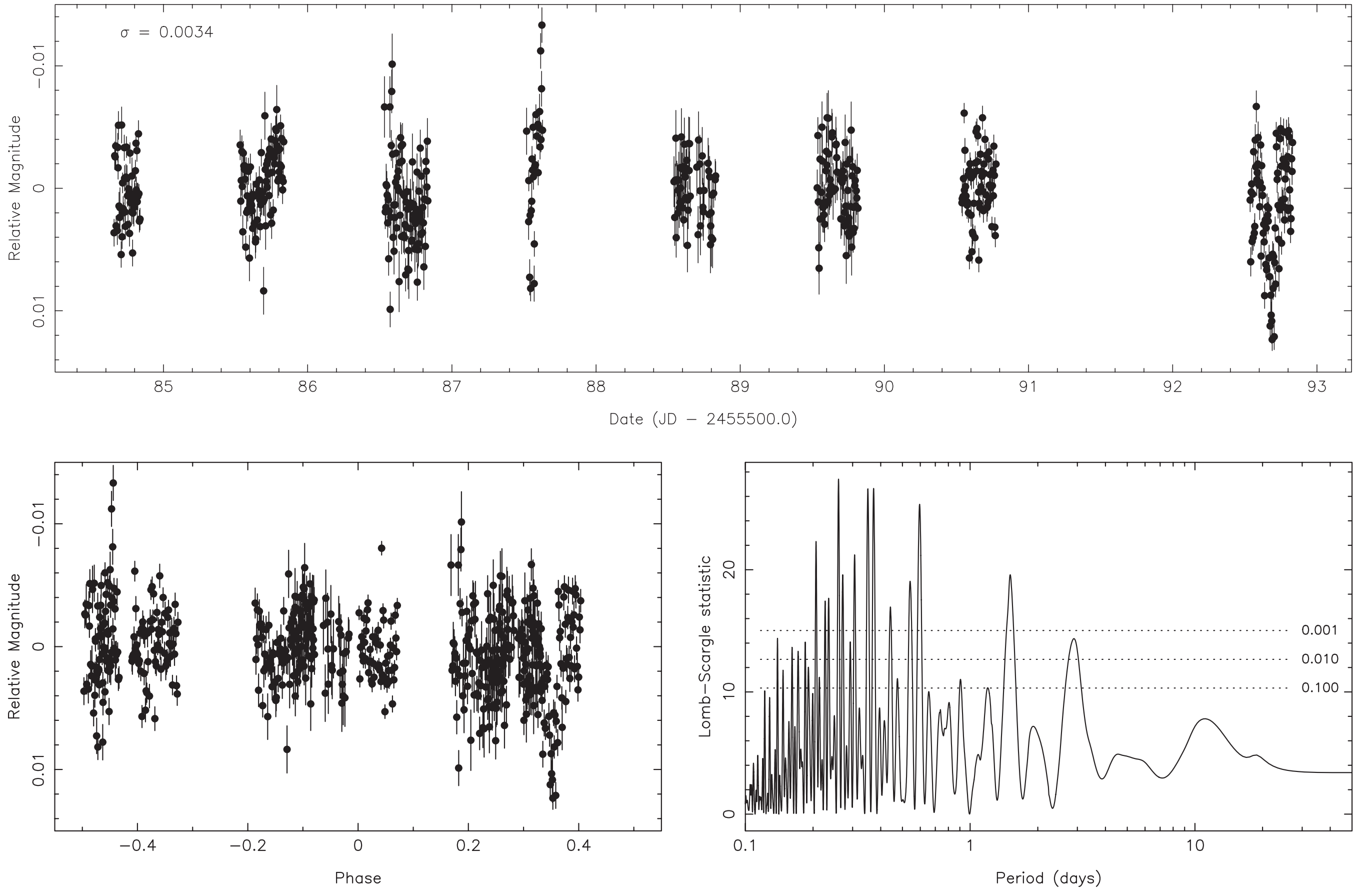

Figure 3. Top panel: photometry of HD 63454 from the January observing run at CTIO, where the data have been binned into 5 minute intervals. Bottom-left panel: all CTIO photometry folded on the best-fit period from Table 2 with the predicted transit time at phase zero. Bottom-right: weighted L–S periodogram of the Janurary CTIO photometry where dotted lines indicate thresholds of false-alarm probabilities.

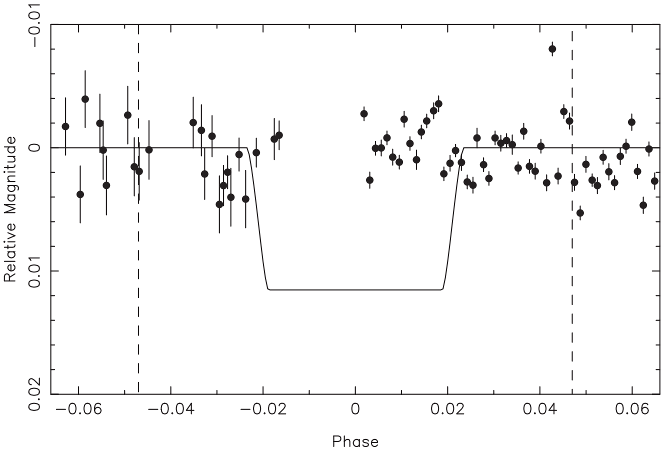

Figure 4. Zoom-in of the CTIO photometry phased on the orbital period with the time of mid-transit at phase zero. The solid line is the predicted transit signature for the predicted stellar/planetary radii and the dashed lines indicate the 1σ extent of the transit window.

point which is the location of the predicted transit mid-point. The vertical dashed lines indicate the 1σ extent of the transit window which is the predicted duration plus twice the transit mid-point uncertainty (see Section 2). In this case, the transit window size is evenly split between the duration and mid-point uncertainty yielding a total transit window size of 0.26 days = 0.094 orbital phase. We calculated the predicted transit signature based upon the analytic models of Mandel & Agol (2002), overplotted as a solid line in the figure.

The conditions on the observing night in 2011 April were exceptional which produced the photometry that dominates the right-hand side of Figure 4. The scatter in these data is larger than what is expected from photon counting statistics. This excess may be due to the nearby faint star but is more likely due to stellar photometric variations. The photometry for that night has a 1σ rms scatter of 2.3 mmag. The predicted transit depth (1.2%) is therefore ruled out at the 5.4σ level. This means that, for a non-transiting planet, the orbital inclination of the planet is restricted to $i < 81\overset{\circ}{.}5$ which results in a lower limit of the planetary mass of $M_p > 0.402\ M_J$. On the other hand, if the planet does transit then the photometric precision rules out planetary radii of $R_p > 0.77\ R_J$. A radius just below this threshold would yield a density of 1.16 g cm^{-3}, resulting in the planet having remarkably similar properties to the large-cored planet HD 149026b (Sato et al. 2005), both in terms of orbital parameters and planetary characteristics.

6. CONCLUSIONS

Understanding the star–planet interaction for systems with hot Jupiters presents an opportunity to further characterize these planets, particularly for transiting exoplanets where both the mass and radius of the planet are known. Detection of magnetic field interactions would yield insight into the internal structure and rotation rate of these planets. The study of HD 63454 presented here was conducted as part of TERMS in order to detect or rule out both stellar variability and transit signatures due to the presence of the planet which has 14% transit probability and a predicted transit depth of 1.2%.

This study includes new HARPS RV data in order to redetermine the phase of the planet during times of photometric monitoring. The requirement for additional photometry in order to rule out a transit based upon the revised orbital parameters demonstrates the need for careful examination of the planetary phase when monitoring predicted transit windows. The *Hipparcos* photometry reveals no long-term variability of the star, although the sampling frequency and photometric precision are inadequate to detect periodicity related to the rotational timescale. The lack of high-frequency variability at the 3 mmag level may indicate that the planet is (1) outside the magnetosphere of the star, or (2) the planetary magnetosphere is very small, or (3) the interaction of the planetary magnetosphere bow shock with the stellar magnetic field is best detected at either higher precision or longer wavelengths (radio). The lack of a transit signature detection indicates that either the mass of the planet is larger than 0.402 M_J or that the radius is less than 0.77 R_J. In the case of the latter, this would imply that the planet has very similar properties to HD 149026b.

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