

A SUPER-EARTH-SIZED PLANET ORBITING IN OR NEAR THE HABITABLE ZONE AROUND A SUN-LIKE STAR

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ABSTRACT

We present the discovery of a super-Earth-sized planet in or near the habitable zone of a Sun-like star. The host is Kepler-69, a 13.7 mag G4V-type star. We detect two periodic sets of transit signals in the 3-year flux time series of Kepler-69, obtained with the *Kepler* spacecraft. Using the very high precision *Kepler* photometry, and follow-up observations, our confidence that these signals represent planetary transits is $>99.3\%$. The inner planet, Kepler-69b, has a radius of $2.24^{+0.44}_{-0.29} R_{\oplus}$ and orbits the host star every 13.7 days. The outer planet, Kepler-69c, is a super-Earth-sized object with a radius of $1.7^{+0.34}_{-0.23} R_{\oplus}$ and an orbital period of 242.5 days. Assuming an Earth-like Bond albedo, Kepler-69c has an equilibrium temperature of 299 ± 19 K, which places the planet close to the habitable zone around the host star. This is the smallest planet found by *Kepler* to be orbiting in or near the habitable zone of a Sun-like star and represents an important step on the path to finding the first true Earth analog.

Key words: planetary systems – stars: fundamental parameters – stars: individual (Kepler-69, KIC 8692861, KOI-172) – stars: statistics – techniques: photometric

Online-only material: color figures

1. INTRODUCTION

NASA’s *Kepler* mission was launched in 2009 with the primary aim of determining the abundance of Earth-sized planets in our Galaxy (Borucki et al. 2010). The 0.95 m optical telescope is in an Earth-trailing heliocentric orbit, providing a stable thermal environment for the production of very high precision photometry. It comprises 42 CCDs with a combined field of view of 115 deg^2 (Koch et al. 2010). The brightness of over 160,000 stars is measured in 29.4 minute integrations, and these data are searched for transiting planets, which appear as periodic dimming in brightness.

While the first true Earth-analog, a planet the size of the Earth and in the habitable zone of a Sun-like star, has yet to be discovered, several important milestones toward achieving this goal have been met using data from the *Kepler* spacecraft. The first planet found by *Kepler* to be orbiting in the habitable zone of a Sun-like star was Kepler-22b (Borucki et al. 2012). With a radius of $2.4 R_{\oplus}$, Kepler-22b likely does not have a rocky surface and is possibly a temperate ocean world (Rogers & Seager 2010). *Kepler* has also been used to discover planets that are Earth-size (Batalha et al. 2011; Fressin et al. 2012) and smaller (Muirhead et al. 2012; Barclay et al. 2013) but these planets are likely to be too hot to host liquid water at their surfaces. The three catalogs of planet candidates published by the *Kepler* mission (Borucki et al. 2011a, 2011b; Batalha et al. 2013) have detailed over 2300 candidates, and have each contained progressively smaller candidates in longer orbits. However, the observation

timespans searched in each catalog (43 days, 137 days, and 1.5 years, respectively) have thus far been too short to allow for three transits (necessary for period confirmation) of a potentially rocky planet in the habitable zone of a Sun-like star.

Kepler-69 has been observed for nearly three years by the *Kepler* spacecraft (observational quarters Q1–Q12) in both long-cadence mode (continuous 29.4 minute integrations), and during Q3–Q6 and one month of Q7 in short-cadence mode (continuous 58.8 s integrations). Transit-like signals in the flux time series, occurring every 13.7 days with a depth of 600 ppm, have been previously reported (Borucki et al. 2011b; Tenenbaum et al. 2012; Batalha et al. 2013). This signal was classified as a Kepler Object of Interest (KOI) with catalog number KOI-172.01. No other planet candidates were detected in the first 1.5 years of observations. Here we report the detection of a second planet candidate, KOI-172.02, with a period of 242.5 days, which was detected in a search of the first two years of observations. Since planets of this size and period cannot currently have their masses measured (by, for instance, radial velocity measurements) and their planetary nature thus confirmed, we rely on statistical analysis of the likelihood that KOI-172.01 and KOI-172.02 are planets for validation of their planetary status.

2. STELLAR PROPERTIES

Kepler-69 appears in the Kepler Input Catalog (KIC; Brown et al. 2011) as KIC 8692861 and has a magnitude of 13.7 in the *Kepler* bandpass. To derive stellar properties, we obtained a

Table 1
Stellar Properties of Kepler-69

Parameter	Value
T_{eff} (K)	5638 ± 168
$\log g$ (dex, cgs units)	4.40 ± 0.15
Metallicity [Fe/H]	-0.29 ± 0.15
Mass (M_{\odot})	$0.810^{+0.090}_{-0.081}$
Radius (R_{\odot})	$0.93^{+0.18}_{-0.12}$
Luminosity (L_{\odot})	$0.80^{+0.37}_{-0.22}$
Density (g cm^{-3})	$1.37^{+0.81}_{-0.55}$
Radial velocity zero point (km s^{-1})	-38.7 ± 0.1

high-resolution spectrum of Kepler-69 using the HIRES spectrograph on the Keck I telescope on 2011 June 23 using the setup of the California Planet Search group (Marcy et al. 2008).

The stellar properties of Kepler-69 were determined by performing a χ^2 fit of the spectrum with a library of 750 observed spectra of F–M type stars that have accurate parallaxes. The library spectra have effective temperatures spanning $T_{\text{eff}} = 3500 \text{ K} - 7500 \text{ K}$ and surface gravities $\log g = 2.0 - 5.0$. The weighted mean of the ten library spectra with the lowest χ^2 values were adopted as the effective temperature, stellar surface gravity, and metallicity of Kepler-69. The weights used were inversely proportional to the Pythagorean distance of stellar parameters from the median value, leading to an iteration that converges quickly. Choosing 10 library matches from which to determine the weighted average offers a statistical buffer against outliers. Best-fitting stellar properties are provided in Table 1.

We also ran a Spectroscopy Made Easy (SME) analysis (Valenti & Fischer 2005) of the Keck spectrum of Kepler-69. The SME results were in excellent agreement with our spectrum matching technique, albeit with lower uncertainties. However, following Torres et al. (2012), we inflated the uncertainties derived from the SME analysis to account for systematic biases. These inflated uncertainties were similar to those found from the spectral matching method described above so we chose to use spectral matching derived parameters in the remaining analysis.

We searched *Kepler* short-cadence data for solar-like oscillations using the method of Huber et al. (2009) but did not detect any. Since oscillation amplitudes scale with stellar luminosity (Kjeldsen & Bedding 1995), evolved subgiant and giant stars show oscillations that are readily detectable with *Kepler* data of 13.7 mag stars. The non-detection of oscillations confirms that Kepler-69 is a dwarf star with a lower limit of $\log g \gtrsim 3.8$, consistent with the stellar properties derived from spectroscopy.

We matched the spectroscopically derived temperature, surface gravity, and metallicity to a fine grid of evolutionary models from the BASTI database (Pietrinferni et al. 2004) in order to estimate the star’s mass and radius. We report the median and the 1σ region of each parameter derived from Monte Carlo simulations using the spectroscopic values in Table 1. Consistent parameters are found using Yonsei-Yale (Demarque et al. 2004) and Dartmouth (Dotter et al. 2008) evolution models. Kepler-69 is a main-sequence G4V star, with a somewhat lower mass and metallicity than the Sun.

3. TRANSIT ANALYSIS

3.1. Transit Detection by the Kepler Pipeline

The Transiting Planet Search (TPS; Jenkins et al. 2010c; Tenenbaum et al. 2012) and Data Validation (DV; Wu et al. 2010) modules of the *Kepler* pipeline (Jenkins et al. 2010b)

identified two transit-like signatures in a search of Q1–Q10 data. The first signature was due to KOI-172.01, a planet candidate previously reported by Borucki et al. (2011b) and Batalha et al. (2013). The second signature was new and had a period of 242.4579 ± 0.0056 days and a depth of 258 ± 19 ppm and has been designated KOI-172.02 (C. J. Burke et al., in preparation). The planet radius provided by the Q1–Q12 DV report for KOI-172.02 was $1.4 R_{\oplus}$. A signal-to-noise ratio (S/N) of 73 was calculated for the transits of KOI-172.01 and 15 for KOI-172.02. The S/Ns for both planet candidates are significantly above the formal threshold of 7.1 (Jenkins et al. 2002), giving us very high confidence that neither of these detections are due to random or correlated noise.

3.2. Light Curve Preparation

There are instrumental features near two of the KOI-172.02 transits. One was a sudden pixel sensitivity dropout due to a cosmic ray hit (Stumpe et al. 2012a), the other is a coronal mass ejection (Thompson et al. 2012). Both aperture photometry and pre-search data conditioned (PDC; Stumpe et al. 2012a; Smith et al. 2012) flux time series data stored at the Mikulski Archive for Space Telescopes (MAST) insufficiently corrected the out-of-transit flux levels around the instrumental signals. This led to a measured transit depth that was underestimated by 20%. We instead chose to use a developmental version of the PDC error-corrected data that relies on error correction via wavelet-based band splitting (Stumpe et al. 2012b). This newly corrected data preserves stellar variability. We removed stellar variability using a numerically efficient discrete cosine transform (Garcia 2010) to implement a non-parametric penalized least squares smoothing of the flux time series. Data from individual quarters were normalized and then combined. Transits were treated as missing when smoothing the data.

3.3. Transit Fitting

We performed a fit of both planet candidates simultaneously using a Mandel & Agol (2002) transit model with quadratic limb darkening. Limb darkening parameters were computed by interpolating the tables of Claret & Bloemen (2011) and kept fixed.

The parameters included in our fit were mean stellar density, photometric zero point, and for each planet the transit epoch, orbital period, the planet-to-star radius ratio, impact parameter, and eccentricity vectors $e \sin \omega$ and $e \cos \omega$, where e and ω are the eccentricity and argument of periastron of the orbit, respectively. We utilized the emcee implementation (Foreman-Mackey et al. 2012) of an affine-invariant Markov Chain Monte Carlo (MCMC) algorithm (Goodman & Weare 2010) to calculate posterior distributions for these parameters. The mean stellar density measured from asteroseismology was used as a Gaussian prior. All other parameters were given uniform priors except for the two eccentricity vectors. Using the $e \sin \omega$ and $e \cos \omega$ parameterization results in an implicit linear prior in e (Ford 2006; Burke et al. 2008; Eastman et al. 2013). We correct for this by enforcing a $1/e$ prior on eccentricity. Our likelihood function is therefore

$$\mathcal{L} = \exp \left(-\frac{\chi^2}{2} + \frac{(\rho_a - \rho_m)^2}{\sigma_\rho^2} - \ln e \right), \quad (1)$$

where ρ_a is the mean stellar density derived from asteroseismology and ρ_m is the model mean stellar density. χ^2 is the usual sum of squared deviation from the model weighted by the variance.

Table 2
Parameters from MCMC Analysis

Parameter	Kepler-69b (KOI-172.01)	Kepler-69c (KOI-172.02)
Stellar density (g cc^{-3})		$1.05^{+0.48}_{-0.27}$
R_p/R_*	$0.02207^{+0.00023}_{-0.00018}$	$0.0168^{+0.00052}_{-0.00052}$
Mid-point of first transit (BJD – 2454833) ^a	$137.8414^{+0.0016}_{-0.0016}$	$150.870^{+0.016}_{-0.014}$
Period (days)	$13.722341^{+0.000035}_{-0.000036}$	$242.4613^{+0.0059}_{-0.0064}$
Impact parameter	$0.15^{+0.17}_{-0.10}$	$0.12^{+0.21}_{-0.09}$
$e \cos \omega$	$0.02^{+0.19}_{-0.14}$	$-0.01^{+0.14}_{-0.16}$
$e \sin \omega$	$-0.07^{+0.09}_{-0.14}$	$-0.02^{+0.08}_{-0.15}$
Planet radius (R_\oplus)	$2.24^{+0.44}_{-0.29}$	$1.71^{+0.34}_{-0.23}$
a/R_*	$21.8^{+2.9}_{-2.1}$	148^{+20}_{-14}
Semimajor axis (AU)	$0.094^{+0.023}_{-0.016}$	$0.64^{+0.15}_{-0.11}$
Inclination (deg)	$89.62^{+0.26}_{-0.45}$	$89.85^{+0.03}_{-0.08}$
Eccentricity	$0.16^{+0.17}_{-0.0010}$	$0.14^{+0.18}_{-0.10}$
Equilibrium temperature (K) ^b	779^{+50}_{-51}	299^{+19}_{-20}
Limb darkening parameters	{0.4012, 0.2627}	

Notes.

^a BJD – 2454833 is the standard *Kepler* time system, known informally as BKJD.

^b Equilibrium temperature assumes an albedo of 0.3 and the thermal recirculation parameter of 1.0.

The median and central 68% of the posterior distribution (equivalent to the 1σ uncertainty) of each parameter are shown in Table 2. Uncertainty in the stellar radius was included as a component of these calculations. The best-fitting transit model and folded time series data are shown in Figure 1. This analysis yielded planet radii of $2.24^{+0.44}_{-0.29}$ and $1.71^{+0.34}_{-0.23} R_\oplus$ for KOI-172.01 and KOI-172.02, respectively.

4. TESTS TO ASSESS THE VALIDITY OF INTERPRETING KOI-172.01 AND KOI-172.02 AS PLANETS

4.1. Tests on the *Kepler* Flux Times Series Data

The *Kepler* photometric data for KOI-172.01 and KOI-172.02 were examined for evidence suggestive of a false positive in the manner described in Batalha et al. (2013). No such evidence was found and hence both candidates were afforded a place within the most recent *Kepler* planet candidate list⁸ (C. J. Burke et al., in preparation). Specifically, odd and even numbered transits have consistent depths, there is no sign of a secondary transit, and there is no significant shift in the photo-centroid of the star in transit relative to out of transit (Jenkins et al. 2010a).

The DV module of the *Kepler* pipeline creates three images: an average out-of-transit image taken from nearby but not during the transit events, an average in-transit image, and a difference image which is the difference between the out-of-transit image and the in-transit image. A fit of the pixel response function (PRF) to the difference image gives the position of the transit source while a fit of the PRF to the out-of-transit image yields the position of the target star. The offset between the difference image position and the target star position can be used to identify false positive scenarios. Conversely, if no significant offset is detected, then the uncertainty in the difference image centroid position can be used to calculate a radius of confusion outside of which a false positive source can be excluded. No significant offsets are measured between the difference image and target position for KOI-172.01. The 3σ radius of confusion

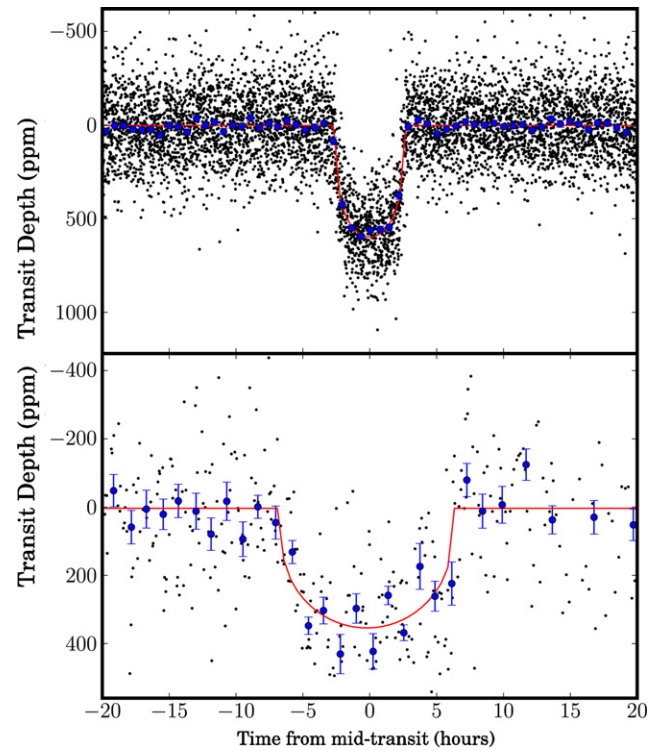


Figure 1. *Kepler* light curve of KOI-172. The upper panel shows the transits of KOI-172.01 folded on the orbital period and the lower panel shows the transits of KOI-172.02. The black points show the observed data and the blue points are binned data. In the upper panel, 100 observed points are included in each bin and in the lower panel 12 point are included in each bin. The uncertainty on the binned data is the standard deviation divided by the square root of the number of points included in the bin. The best fitting transit models are shown overplotted in red.

(A color version of this figure is available in the online journal.)

was measured by DV at 0.16 arcsec. Only two transits were included in the PRF centroid offset metric in the DV report for KOI-172.02 owing to data artifacts and transits of KOI-172.01 occurring near the transits of KOI-172.02. We wished to use

⁸ The *Kepler* planet catalog and DV reports are hosted at the NASA Exoplanet Archive, <http://exoplanetarchive.ipac.caltech.edu/>.

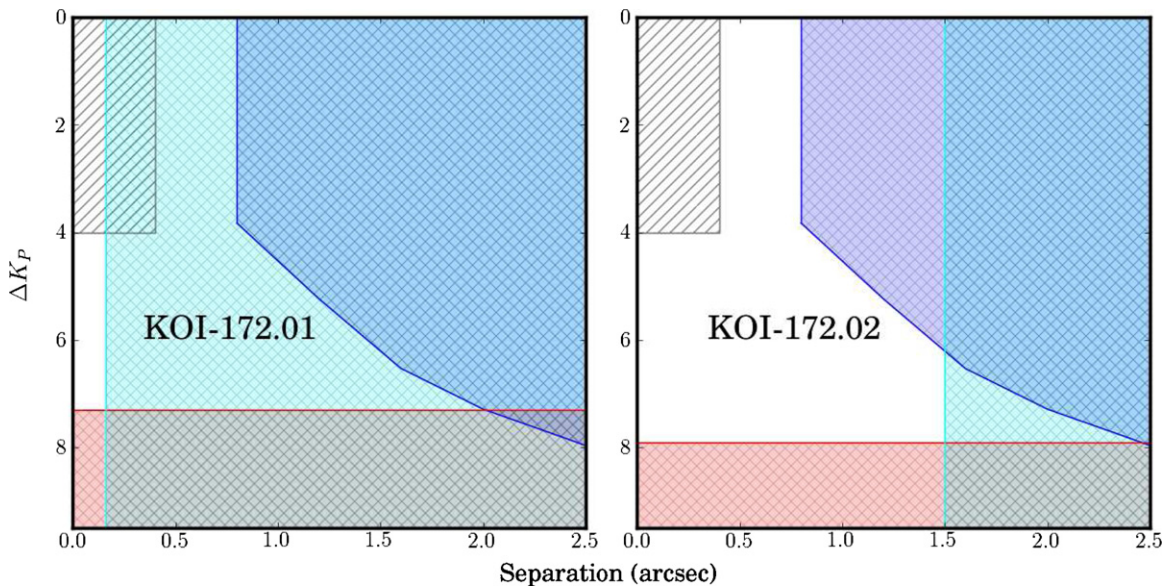


Figure 2. Regions of parameter space where a false positive source can be excluded are shown colored. The exclusion region from the transit depth is shown in red, from the UKIRT imaging in blue and from the centroids in cyan. The white hashed region shows the constraints from the Keck spectral analysis. In this region, contaminating stars are only allowed if they have a radial velocity within 10 km s^{-1} . The region in white is not excluded and must therefore be accounted for in our false positive analysis.

(A color version of this figure is available in the online journal.)

all five transits of KOI-172.02 in our centroid analysis so we created difference images in the same manner used by the *Kepler* pipeline (Bryson et al. 2013) but included all observed transits of KOI-172.02. The significance of the offset from the remaining images was less than 3σ which is used as the warning threshold (Batalha et al. 2013; Bryson et al. 2013). The radius of confusion was estimated to be 1.5 arcsec. Given the above described tests, there is no reason to suspect KOI-172.01 or KOI-172.02 are false positives based on the *Kepler* data.

We measured a transit depth for KOI-172.02 of 350 ppm from the MCMC analysis. The faintest a star could be and still produce a transit of this depth can be calculated if we assume a total eclipse of that background star (Chaplin et al. 2013). Under this assumption, the faintest a false positive star could be is 7.9 mag fainter than Kepler-69. This is the limit we use in all false positive calculations for KOI-172.02. For KOI-172.01 the transit depth is 597 ppm, which sets the maximum brightness difference between the target star and a false positive of 7.3 mag.

4.2. Imaging of Kepler-69

We obtained optical *V*-band images of Kepler-69 using the Nickel 1 m telescope at Lick Observatory and searched for nearby stars. No stars are seen 2–5 arcsec from Kepler-69 brighter than 19th magnitude; stars closer than 2 arcsec could not be ruled out. Kepler-69 has a *V*-band magnitude of 14.0 (Everett et al. 2012), therefore we cannot exclude stars between $V = 19\text{--}21.9$ for KOI-172.02 and $V = 19\text{--}21.3$ for KOI-172.01 based on the Lick image and the transit depths.

There is a UK Infrared Telescope (UKIRT) *J*-band image of a field containing Kepler-69. The closest star is 3.2 arcsec west of Kepler-69 and is 9 mag fainter. This nearby star can be ruled out as the source of the transit signal from either planet candidate based on the PRF centroids. A magnitude dependent radius of confusion around Kepler-69 was calculated for use in false positive analysis. This confusion radius was converted to the *Kepler* magnitude system (Brown et al. 2011; Howell et al. 2012) and is shown in blue in Figure 2.

4.3. Looking for a Second Star in HIRES Spectra

The slit width used to collect the HIRES spectrum of Kepler-69 was 0.87 arcsec. This allowed us to search the HIRES spectrum for additional stars within 0.43 arcsec of the target. We calculated the best-fitting two-spectrum model using observed spectra with T_{eff} ranging from 3500 to 6000 K. We searched over a range of secondary star radial velocities and flux ratios relative to the target star. No second star was seen in the spectra down to the confusion limit of $\Delta K_P = 4.0$. We then injected a range of observed spectra into the spectrum of Kepler-69. Given that we measure a radial velocity for Kepler-69 of $-38.7 \pm 0.1 \text{ km s}^{-1}$, virtually all sufficiently bright background stars would have been detected. G- and K-dwarf physical companions to Kepler-69 that are further than approximately 20 AU could evade detection owing to them having a radial velocity that we could not distinguish from Kepler-69. Companions with spectral type later than M0 are detected at any distance from the target (subject to falling into the spectrograph’s slit) provided they are brighter than $\Delta K_P = 4.0$.

5. ON THE PROBABILITY THAT KOI-172.01 AND KOI-172.02 ARE FALSE POSITIVES

In this section, we first consider the probability that KOI-172.01 and KOI-172.02 are in fact transits or eclipses of a background star. We find that the chance of this occurring for KOI-172.01 is 0.01% and for KOI-172.02 it is 0.04%. We are able to rule out the transit-like signals being due to a hierarchical triple stellar system and therefore validate KOI-172.01 and KOI-172.02 as confirmed planets.

We then go on to look at whether either of the two planets orbit a physical companion star. While for KOI-172.01 the probability of this is 0.01%, for KOI-172.02 it is $<1\%$ and hence cannot be definitively ruled out, but is unlikely.

5.1. False Positive Scenarios Considered

Given that the KOI-172.01 and KOI-172.02 detections are unlikely to be due to noise (Jenkins et al. 2002), we can safely assume that they either represent planets or astrophysical false positives. Scenarios that could cause a transit-like signal that are not caused by a planet orbiting Kepler-69 are:

1. Stellar binaries with grazing eclipses (the impact parameter > 1).
2. Background eclipsing binaries.⁹
3. Background star-planet systems.
4. An eclipsing binary physically associated with Kepler-69 in a hierarchical stellar triple system.
5. A planet orbiting a stellar physical companion of Kepler-69.

We are immediately able to dismiss scenarios 1 and 4 because the best-fitting models representing these scenarios fit the observed data worse than the best-fitting transiting planet model at a level $> 3\sigma$. This is because a stellar eclipse across Kepler-69 or a physical companion would be more V-shaped than we observe. Additionally, these scenarios are predicted to be very uncommon for sub-Jupiter-sized planet candidates (Fressin et al. 2013). The remaining false positive discussion is restricted to scenarios 2, 3, and 5.

5.2. Background False Positive Scenarios

To assess the probability that the transit-like signals we detect are not associated with the Kepler-69 system but are on a background star, we simulate the stellar background population that could be responsible. We simulated the number of stars within 1 deg of Kepler-69 using the Besançon Galaxy model with kinematics enabled (Robin et al. 2003). The Galactic model predicts there are 432,118 stars, of which 44,185 fall in the brightness range $14.0 < V < 22.0$ and are not excluded by the secondary star test performed on the Keck spectrum. We integrated the area shown in white in Figure 2 to calculate the undetected stellar population in the background of KOI-172.02. The estimated number of stars in the background is 0.018. If we now consider that only 2.6% of stars observed by *Kepler* host either a transiting planet candidate or are an eclipsing binary, then excluding contact binaries (Batalha et al. 2013; Slawson et al. 2011; C. J. Burke et al., in preparation), the predicted number of background stars which could cause a false positive is 0.00046.

We used a Bayesian approach similar to that applied by Fressin et al. (2012) and Barclay et al. (2013) to the validation of the planets orbiting Kepler-20 and Kepler-37 to quantify the false positive probability. This technique compares the *a priori* chance of finding a planet the size of KOI-172.02 (the planet prior) to that of finding a background false positive. The ratio of the planet prior to the false positive probability is used to calculate our confidence in the planet interpretation. The population of super-Earth-sized planets orbiting with periods longer than 85 days is not well constrained. We assume that the super-Earth occurrence rate is the same at long orbital periods as it is at shorter orbital periods when period is measured in logarithmic units. There is evidence that the occurrence rate of super-Earth-sized planets is even high at longer orbital periods than at short periods. For example Cassan et al. (2012) find $62^{+35}_{-37}\%$ of stars host a super-Earth-mass planet. Therefore,

using the statistics of Fressin et al. (2013), who derived a super-Earth occurrence rate of $23\% \pm 2.4\%$, may well lead to an underestimate of our planet prior.

There are 666 super-Earth-sized ($1.25\text{--}2.0 R_{\oplus}$) planet candidates tabulated in Batalha et al. (2013). However, Fressin et al. (2013) predict that 8.8% of these are false positives which provides an estimated number of super-Earths found by *Kepler* of 607. The catalog of Batalha et al. (2013) was based on continuous (Q1–Q6) observations of 138,253 stars. Therefore, the occurrence rate of transiting super-Earth-sized planets is 0.0044 per star. We can compare this to the background/foreground false positive population which is 0.00046, as explained above. If KOI-172.02 were the only planet candidate associated with Kepler-69, then the likelihood of it being a true planet would be $0.0044/(0.0044 + 0.00046) = 0.91$. However, KOI-172.02 is in a two planet candidate system. As shown by Lissauer et al. (2012), having multiple transiting planet candidates associated with a star increases the probability that these candidates are real planets by a factor of ~ 15 compared to single planet candidate systems. This *multiplicity boost* increases our confidence that KOI-172.02 is a bona fide planet physically associated with the Kepler-69 system to 99.3%.

We note that Kepler-69 has a lower metallicity than the Sun and for large planets a low metal content has been shown to hinder planet occurrence (e.g., Mayor et al. 2011). However, there appears to be no link between planet occurrence and stellar metallicity (Buchhave et al. 2012) for transiting super-Earth-sized planets. Therefore, we do not factor the stellar metallicity into our false positive calculations.

The centroid confusion radius for KOI-172.01 is much smaller than for KOI-172.02 (as shown in Figure 2). Using the approach outlined above, our confidence is 99.9% that KOI-172.01 is a planetary mass body physically associated with the Kepler-69 system. We can therefore conclude that the signals we observe are due to bona fide planets. The inner and outer planets are named Kepler-69b and Kepler-69c, respectively.

5.3. The Possibility That the Planets in the Kepler-69 System Orbit a Physical Companion

While the above analysis leads us to conclude that Kepler-69b and Kepler-69c are both substellar bodies physically associated with the target system, this does not exclude a scenario where one or both of the planets orbit a fainter stellar companion to Kepler-69.

We performed a series of MCMC transit analyses with no prior on the stellar density with the aim of constraining the range of stellar types the planets could orbit. First, we assumed that both planets orbit the same star. If this is the case, then this star would have a stellar density of $1.04^{+0.53}_{-0.31} \text{ g cm}^{-3}$ with a 3σ upper limit of 3.6 g cm^{-3} . This rules out both planets orbiting a star with a radius less than $0.64 R_{\odot}$, where the radius is calculated using Dartmouth isochrones (Dotter et al. 2008) and assumes Kepler-69 and stellar companion coevolved. We tried including a fixed dilution in the transit depth of 98% to simulate both planets being around a star 1/50th the brightness of the primary star in the system. In this case, we found a 3σ upper limit on the stellar density of 2.8 g cm^{-3} . However, a companion hosting a transit whose light is diluted by 98% should have a density of 9.7 g cm^{-3} based on isochrones, therefore we can rule out a scenario where both planets orbits a much fainter companion. If both planets orbit a companion, then it must be a G or early K-type star.

⁹ The phrase background stars is used to refer to stars that appear fainter than Kepler-69 and are not physically associated. They may be either in the foreground or background with respect to Kepler-69.

We now consider the case that both planets orbit different stars. Fitting only the transits of Kepler-69b gave a stellar density upper limit of 6.2 g cm^{-3} which would place Kepler-69b around a star with a radius of at least $0.48 R_{\odot}$. This rules out Kepler-69c orbiting a star with a spectral type later than K9V. Fitting just for Kepler-69c implies a star with a mean stellar density of $1.3^{+1.1}_{-1.0} \text{ g cm}^{-3}$ and the 3σ upper limit on density is 8.7 g cm^{-3} . Including a dilution in the transit depth of 98% loosened our 3σ upper limit on the stellar density to 15.5 g cm^{-3} . A star with a density of 15.5 g cm^{-3} that coevolved with Kepler-69 would have a radius of $0.31 R_{\odot}$ —an M2-type star. Therefore, in the case of a physical companion, Kepler-69c cannot orbit a star cooler than an M2-type.

To quantify the probability that either of the planets orbit a companion star, we constructed three Monte Carlo simulations to estimate the properties of a stellar companion with different assumptions: both planets orbit a companion to Kepler-69; Kepler-69b orbits Kepler-69 and Kepler-69c orbits a companion; and Kepler-69c orbits Kepler-69 and Kepler-69b orbits a companion.

In the simulations, we assume the orbital period is described by a lognormal distribution with mean $\log P = 5.03$ and standard deviation $\sigma_{\log P} = 2.28$ where period is in days (Raghavan et al. 2010) and eccentricity is uniform from zero to one. The primary-to-secondary mass ratio q is assumed to be uniformly distributed (this approximates the distribution found by Halbwachs et al. 2003). The argument of periastron is taken to be uniformly distributed. We ran the simulation 10^7 times. At each loop in the simulation, we calculated the radius, density, and brightness of the companion based on Dartmouth isochrones (Dotter et al. 2008). We calculated the binary separation from the orbital period and mass ratio. The radial velocity at the point of observation of the secondary was determined by calculating a radial velocity curve and selecting the time of observation at random.

We then calculated the proportion of secondary scenarios from our simulation that are unphysical or excluded based on observations. Unphysical scenarios are those where the binary separation is too small to allow a stable planetary orbit of 242.4 days (Rabl & Dvorak 1988; Holman & Wiegert 1999). We used the diluted MCMC transit analyses' 3σ upper limit on stellar density to exclude companions that are too dense or faint. Using the constraint from the Keck spectrum, if a companion had a brightness within 4 mag of Kepler-69 and a radial velocity difference between it and the primary of $> 10 \text{ km s}^{-1}$ (the limit from our analysis of the Keck spectrum), then it was excluded. Companions that would be seen by the J -band image or would induce a detectable centroid shift were also excluded. We find that a companion star is able to host Kepler-69b less than 0.01% of the time. Therefore, we are confident that Kepler-69b orbits the target star. However, in 1.9% of the simulations, Kepler-69 has a stellar companion capable of hosting Kepler-69c. If we assume that in scenarios with a viable planet hosting companion, half the time the planet orbits the primary and half the secondary, then our confidence that Kepler-69c orbits the primary is 99.1%. However, no *multiplicity boost* is included in the above calculation. It is unclear whether a companion is more likely to host transiting planets if the primary hosts transiting planets compared to a field star. However, if we were to apply this boost, the probability that Kepler-69c orbits Kepler-69 is 99.93%. The true probability that Kepler-69c orbits a companion star lies somewhere between 0.06% and 0.9%.

While we cannot conclusively rule out the possibility that Kepler-69c orbits a smaller star and therefore is larger and cooler, the chances are low. With more follow-up observations we may be able to further restrict the allowed parameter space and increase our confidence that Kepler-69c orbits the primary star. Specifically, continued non-detections in future radial velocity observations will increase the size of the region around Kepler-69 where we can rule out any companion star, while a deep adaptive optics observations can help rule out companions further from the star than around 0.5 arcsec.

In the remaining analysis, we will assume that Kepler-69c orbits the target star.

6. ON THE COMPOSITION AND TEMPERATURE OF KEPLER-69c

It is not clear where the boundary between the radius of a rocky (or terrestrial) planet and that of a giant volatile rich planet lies. There is very likely not an absolute boundary but a range of cutoffs which depend on the initial composition of the protoplanetary disk (Valencia et al. 2007). In any case, the 1σ uncertainty we determine for the radius of Kepler-69c makes predicting its composition difficult. The 1σ lower bound of $1.48 R_{\oplus}$ may well represent a rocky planet but the upper bound of 2.04 probably represents a fairly volatile rich planet. If Kepler-69c were volatile rich, then it could be a water world and quite unlike any planet in our Solar System.

To estimate the equilibrium temperature of Kepler-69c, we must make some assumptions about the albedo and the thermal energy redistribution of the planet. We use the same equation as used in Batalha et al. (2013) to calculate equilibrium temperature,

$$T_{\text{eq}} = T_{\text{eff}}(R_{\star}/2a)^{1/2}[f(1 - A_B)]^{1/4}, \quad (2)$$

T_{eff} is the effective temperature of the star, R_{\star} is the stellar radius, a is the planet's semimajor axis, f is the thermal redistribution parameter (where $f = 1$ refers to full thermal recircularization), and A_B is the Bond albedo. In the Batalha et al. (2013) *Kepler* planet candidate catalog, they assume $f = 1$ and $A_B = 0.3$ (the same albedo as Earth). Using these values results in a temperature of $299^{+19}_{-19} \text{ K}$, significantly lower than the boiling point of water. If we assume a lower Bond albedo of 0.1 (similar to that of Mercury), then the temperature of the planet increases to $318^{+20}_{-21} \text{ K}$, still in a regime where water could exist in a liquid form (neglecting the effects of an atmosphere). In Figure 3, we show the range of equilibrium temperatures that Kepler-69c would have as a function of A_B . With a reasonably thick atmosphere and a rotation rate similar to Earth, Kepler-69c would have a thermal redistribution parameter of $f \sim 1$ (for reference Earth has a value of $f = 1.1$ and for Venus $f \sim 1$).

An atmosphere can dramatically increase the surface temperature of a planet (c.f. Venus). Kasting (2011) suggests the upper boundary on the temperature of a habitable planet lies around 310 K —Kepler-69c likely falls below this limit if it has a similar or higher albedo than Earth. However, Selsis et al. (2007) puts the limit at a more conservative 270 K , Kepler-69c would require an albedo greater than 0.5 to satisfy this requirement. In Figure 3, we have plotted the habitable range suggested by Kasting (2011). We have also plotted points corresponding to Venus, Earth and Mars. Kepler-69c likely falls within the habitable zone for moderate albedos if we use the limit of Kasting (2011) although it would require a fairly high albedo to be habitable according to the limit of Selsis et al. (2007).

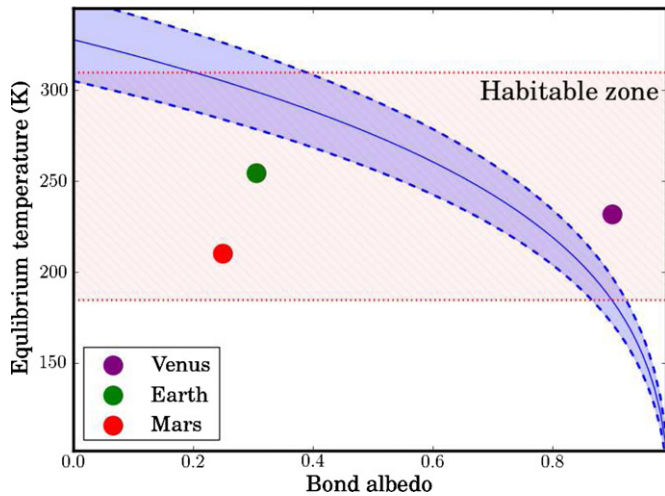


Figure 3. Equilibrium temperature of Kepler-69c as a function of Bond albedo. The blue shaded region shows the 1σ range assuming $f = 1.0$ where uncertainties were calculated from the MCMC chains. We expect f to be close to unity if Kepler-69c has an atmosphere similar to that of Earth. Venus, Earth and Mars are plotted for comparison. The habitable zone as suggested by Kasting (2011) is shaded in red and bounded by the dashed lines. Kepler-69c falls near or within the habitable zone with reasonable assumptions of its albedo.

(A color version of this figure is available in the online journal.)

The above analysis assumes that Kepler-69c has a circular orbit. From our MCMC transit analysis we find Kepler-69c may be highly eccentric—the 3σ upper limit is $e = 0.79$. The apastron distance is $0.73^{+0.22}_{-0.13}$ AU at which distance Kepler-69c would have an equilibrium temperature of 282^{+19}_{-31} K. However, Kepler-69c would have an equilibrium temperature of 322^{+47}_{-21} K at periastron. If the planet is indeed on an eccentric orbit, then it may experience high seasonal temperature variations. However, a Kepler-69c is most likely on a reasonably circular orbit and therefore will probably not go through dramatic freeze-thaw cycles.

7. CONCLUSIONS

In this paper, we report the discovery of two transit-like signals in the light curve of Kepler-69 which we show are bona fide planets orbiting a Sun-like star. While we are confident at the 99.9% level that Kepler-69b orbits the target star, there is a slight possibility ($<0.9\%$) that Kepler-69c orbits a physical companion star to Kepler-69.

With a 1σ uncertainty on the stellar radius and hence the radius of Kepler-69c of 17%, we cannot conclusively say whether the planet is rocky or has a high volatile content (Valencia et al. 2007).

The temperature of Kepler-69c probably falls close to its host star's habitable zone but a degree of inference must be made as to the planet's albedo in order to determine an equilibrium temperature. With reasonable assumptions it is possible that liquid water could exist in significant quantities on the surface of this planet.

Kepler-69c represents the first discovery of a super-Earth in the habitable zone of a Sun-like star. The work represents a progressive step on the road to detecting the first truly Earth-like planet orbiting a star like our Sun.

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REFERENCES

- Barclay, T., Rowe, J. F., Lissauer, J. J., et al. 2013, *Natur*, **494**, 452
 Batalha, N. M., Borucki, W. J., Bryson, S. T., et al. 2011, *ApJ*, **729**, 27
 Batalha, N. M., Rowe, J. F., Bryson, S. T., et al. 2013, *ApJS*, **204**, 24
 Borucki, W. J., Koch, D., Basri, G., et al. 2010, *Sci*, **327**, 977
 Borucki, W. J., Koch, D. G., Basri, G., et al. 2011a, *ApJ*, **728**, 117
 Borucki, W. J., Koch, D. G., Basri, G., et al. 2011b, *ApJ*, **736**, 19
 Borucki, W. J., Koch, D. G., Batalha, N., et al. 2012, *ApJ*, **745**, 120
 Brown, T. M., Latham, D. W., Everett, M. E., & Esquerdo, G. A. 2011, *AJ*, **142**, 112
 Bryson, S. T., et al. 2013, PASP, submitted (arXiv:1303.0052)
 Buchhave, L. A., Latham, D. W., Johansen, A., et al. 2012, *Natur*, **486**, 375
 Burke, C. J., McCullough, P. R., Valenti, J. A., et al. 2008, *ApJ*, **686**, 1331
 Casali, M., Adamson, A., Alves de Oliveira, C., et al. 2007, *A&A*, **467**, 777
 Cassan, A., Kubas, D., Beaulieu, J.-P., et al. 2012, *Natur*, **481**, 167
 Chaplin, W. J., Sanchis-Ojeda, R., Campante, T. L., et al. 2013, *ApJ*, **766**, 101
 Claret, A., & Bloemen, S. 2011, *A&A*, **529**, A75
 Demarque, P., Woo, J.-H., Kim, Y.-C., & Yi, S. K. 2004, *ApJS*, **155**, 667
 Dotter, A., Chaboyer, B., Jevremović, D., et al. 2008, *ApJS*, **178**, 89
 Eastman, J., Gaudi, B. S., & Agol, E. 2013, *PASP*, **125**, 83
 Everett, M. E., Howell, S. B., & Kinemuchi, K. 2012, *PASP*, **124**, 316
 Ford, E. B. 2006, *ApJ*, **642**, 505
 Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2012, PASP, in press (arXiv:1202.3665)
 Fressin, F., Torres, G., Charbonneau, D., et al. 2013, *ApJ*, **766**, 81
 Fressin, F., Torres, G., Rowe, J. F., et al. 2012, *Natur*, **482**, 195
 Garcia, D. 2010, *Comput. Stat. Data Anal.*, **54**, 1167
 Goodman, J., & Weare, J. 2010, *Comm. App. Math. Comp. Sci.*, **5**, 65
 Halbwachs, J. L., Mayor, M., Udry, S., & Arenou, F. 2003, *A&A*, **397**, 159
 Hambly, N. C., Collins, R. S., Cross, N. J. G., et al. 2008, *MNRAS*, **384**, 637
 Hewett, P. C., Warren, S. J., Leggett, S. K., & Hodgkin, S. T. 2006, *MNRAS*, **367**, 454
 Holman, M. J., & Wiegert, P. A. 1999, *AJ*, **117**, 621
 Howell, S. B., Rowe, J. F., Bryson, S. T., et al. 2012, *ApJ*, **746**, 123
 Huber, D., Stello, D., Bedding, T. R., et al. 2009, *CoAst*, **160**, 74
 Jenkins, J. M., Borucki, W. J., Koch, D. G., et al. 2010a, *ApJ*, **724**, 1108
 Jenkins, J. M., Caldwell, D. A., & Borucki, W. J. 2002, *ApJ*, **564**, 495
 Jenkins, J. M., Caldwell, D. A., Chandrasekaran, H., et al. 2010b, *ApJL*, **713**, L87
 Jenkins, J. M., Chandrasekaran, H., McCauliff, S. D., et al. 2010c, *Proc. SPIE*, **7740**, 77400D
 Kasting, J. F. 2011, Joint Meeting of the Exoplanet and Cosmic Origins Program Analysis Groups (ExoPAG and COPAG), Baltimore, MD, <http://exep.jpl.nasa.gov/exopag/exopagCOPAGJointMeeting/>
 Kjeldsen, H., & Bedding, T. R. 1995, *A&A*, **293**, 87
 Koch, D. G., Borucki, W. J., Basri, G., et al. 2010, *ApJL*, **713**, L79
 Lissauer, J. J., Marcy, G. W., Rowe, J. F., et al. 2012, *ApJ*, **750**, 112
 Mandel, K., & Agol, E. 2002, *ApJL*, **580**, L171
 Marcy, G. W., Butler, R. P., Vogt, S. S., et al. 2008, *PhST*, **130**, 014001
 Mayor, M., Marmier, M., Lovis, C., et al. 2011, arXiv:1109.2497
 Muirhead, P. S., Johnson, J. A., Apps, K., et al. 2012, *ApJ*, **747**, 144

- Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2004, [ApJ](#), **612**, 168
- Rabl, G., & Dvorak, R. 1988, [A&A](#), **191**, 385
- Raghavan, D., McAlister, H. A., Henry, T. J., et al. 2010, [ApJS](#), **190**, 1
- Robin, A. C., Reyl  , C., Derri  re, S., & Picaud, S. 2003, [A&A](#), **409**, 523
- Rogers, L. A., & Seager, S. 2010, [ApJ](#), **716**, 1208
- Selsis, F., Kasting, J. F., Levrard, B., et al. 2007, [A&A](#), **476**, 1373
- Slawson, R. W., Pr   a, A., Welsh, W. F., et al. 2011, [AJ](#), **142**, 160
- Smith, J. C., Stumpe, M. C., Van Cleve, J. E., et al. 2012, [PASP](#), **124**, 1000
- Stumpe, M. C., Smith, J. C., Van Cleve, J. E., et al. 2012a, [PASP](#), **124**, 985
- Stumpe, M. C., Smith, J. C., Van Cleve, J., et al. 2012b, in Bulletin of the American Astronomical Society, vol. 44, AAS 220th Meeting Abstracts, [conference poster 330.04](#)
- Tenenbaum, P., Christiansen, J. L., Jenkins, J. M., et al. 2012, [ApJS](#), **199**, 24
- Thompson, S. E., Christiansen, J. L., & Jenkins, J. M. 2012, Kepler Data Release 17 Notes, KSCI-19057-001
- Torres, G., Fischer, D. A., Sozzetti, A., et al. 2012, [ApJ](#), **757**, 161
- Valencia, D., Sasselov, D. D., & O'Connell, R. J. 2007, [ApJ](#), **665**, 1413
- Valenti, J. A., & Fischer, D. A. 2005, [ApJS](#), **159**, 141
- Wu, H., Twicken, J. D., Tenenbaum, P., et al. 2010, [Proc. SPIE](#), **7740**, 774019