Planet Hunters: The First Two Planet Candidates Identified by the Public using the Kepler Public Archive Data^{*}

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26 September 2011

ABSTRACT

Planet Hunters is a new citizen science project, designed to engage the public in an exoplanet search using NASA Kepler public release data. In the first month after launch, users identified two new planet candidates which survived our checks for false-positives. The follow-up effort included analysis of Keck HIRES spectra of the host stars, analysis of pixel centroid offsets in the Kepler data and adaptive optics imaging at Keck using NIRC2. Spectral synthesis modeling coupled with stellar evolutionary models yields a stellar density distribution, which is used to model the transit orbit. The orbital periods of the planet candidates are 9.8844 ± 0.0087 days (KIC 10905746) and 49.7696 ± 0.00039 (KIC 6185331) days and the modeled planet radii are 2.65 and 8.05 R_{\oplus}. The involvement of citizen scientists as part of Planet Hunters is therefore shown to be a valuable and reliable tool in exoplanet detection.

Key words: planetary systems – stars: individual (KIC 10905746, KIC 6185331, KIC 8242434, KIC 11820830,, KIC 11904734, KIC 8043052, KIC 12009347, KIC 4913000, KIC 9097892)

 * This publication has been made possible by the participa- \odot 0000 RAS

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1 INTRODUCTION

The past decade has witnessed an explosion in the number of known planets beyond our solar system. From the ground, planet searches using techniques that include Doppler observations, transit photometry, microlensing, and direct imaging have identified more than 500 exoplanets (Schneider 2011; Wright et al. 2011). These observations have provided a wealth of information, including constraints on dynamical interactions in multiplanet systems, non-coplanar orbits of hot Jupiters, and atmospheric properties of transiting gas giant planets. The combination of Doppler and photometric measurements of transiting planets is particularly informative because it yields planet densities and enables theoretical modeling of the interior structure and composition of exoplanets.

The Kepler Mission is monitoring more than 150,000 stars with unprecedented 29-minute observing cadence (Jenkins et al. 2010) and a relative photometric precision approaching 20 ppm in 6.5 hours for Kp=12 mag stars to search for transiting planets. After just one year of operation, Borucki et al. (2010a) announced the detection of 706 transiting planet candidates based on the first quarter (Q1) data. On 2011 February 1, one month before the two-year anniversary of launch, the total number of planet candidates increased to more than 1200 (Borucki et al. 2011). The Q1 data were released into the public archive in 2010 June, followed by a release of second quarter (Q2) data in 2011 February. The public archive is hosted by the Multi-mission Archive at STScI (MAST¹) and the NASA/IPAC/NExSci Star and Exoplanet Database (NStED²).

Although there are more than 1200 Kepler candidates, only 1 - 2% of these are confirmed planets with measured masses from Doppler observations (Batalha et al. 2011; Borucki et al. 2010b). These are challenging confirmations. The Kepler stars are faint compared to stars in ground based radial velocity surveys and most of the Kepler candidates have radii consistent with Neptune like planets, so most of the stellar reflex velocities are comparable to the formal measurement errors. Transit timing variations (Holman et al. 2010; Lissauer et al. 2011) offer a novel way to derive planet masses, but require multi-planet systems with measureable non-Keplerian orbital perturbations.

The Kepler team has developed sophisticated algorithms for detecting transits by fitting and removing periodic or quasi-periodic stellar variability (with low and high frequencies). In addition to modeling out background variability, the Kepler pipeline stitches together data from different observing quarters by determining the median flux from adjacent observing windows and using polynomial fits across the boundary. The Kepler team developed the Transit Planet Search (TPS) algorithm, a wavelet-based adaptive filter to identify a periodic pulse train with temporal widths ranging from 1 to 16 hours (Jenkins 2002; Jenkins et al. 2010). Photometric uncertainties are assessed to identify light curves with phase-folded detection statistics exceeding 7.1-sigma. This threshold was selected so that given the number of required independent statistical tests per star,

project. Their contributions are individually acknowledged at http://www.planethunters .org/authors † E-mail: debra.fischer@yale.edu

¹ http://archive.stsci.edu/

² http://nsted.ipac.caltech.edu

four years of data for the entire set of Kepler targets could be robustly searched for orbital periods up to two years.

While the human brain is exceptionally good at detecting patterns, it is impractical for a single individual to review each of the ~ 150,000 light curves in every quarterly release of the Kepler database. However, crowd-sourcing this task has appeal because human classifiers have a remarkable ability to recognize archetypes and to assemble groups of similar objects, while disregarding obvious glitches that can trip up computer algorithms. This skill has recently been put to use in a wide range of scientific fields, from galaxy morphology to protein folding. To engage these uniquely human talents, and to give the public the opportunity to participate in an exciting exoplanet search, we developed Planet Hunters³ to present Kepler light curves to the public.

Planet Hunters is a new addition to the successful Zooniverse network of Citizen Science Alliance projects (Lintott et al. 2008, 2011), and the first Zooniverse project to present time series data (rather than images) to the public. The site was launched on 2010 December 16, and after six months, more than 40,000 users have made more than 3 million light curve classifications. Here we describe the layout of the site and two new planet candidates identified by the public using the PlanetHunter interface.

2 IDENTIFYING TRANSITS

The Planet Hunters website makes use of the Zooniverse⁴ toolset, which now supports a wide variety of citizen science projects. Its primary function is to serve up assets - in this case \sim 33 day flux-corrected light curves derived from the Kepler data - to an interface, and to collect user-generated interactions with these data.

Previous Zooniverse projects have included a separate tutorial to assist volunteers. While the Planet Hunters website includes such a tutorial, initial guidance is given within the interface, accessed via a single click from the site home page. Volunteers see a light curve with example transits, and can then begin to classify data. Users who have not registered with the Zooniverse, or who are not logged in, can begin classifying but receive frequent reminders to log in. The site supports prioritization of the light curves; for logged-in users viewing the Q1 data discussed in this paper, simulated or already identified transits were shown 5%of the time. A curve associated with a dwarf star was then shown 66% of the remaining time, and one associated with a giant star 33% of the time. Once a category (i.e., simulated light curve, dwarf or giant star) has been selected, a light curve is chosen randomly from the top ten scoring assets in that category. (The score is the number of transits marked on each curve). Once curves have been classified by ten volunteers, they are removed from the list. The results are made available to the science team immediately via a private website.

The actual classification proceeds via a decision tree. In the first step, users are asked whether the light curve is variable or quiet (icons and help buttons provide visual prompts). The user is then asked whether any transit features are present and has the option to zoom in and out of particular areas of the light curve. If transit features are found, the user can mark them with boxes as demonstrated in Figure 1. In some cases, the transit features seen are synthetic transits of known period and radius, which are used to assess the completeness of the user classifications.

After all transits are marked, the user has the option to discuss this particular star on the Planet Hunters Talk site and connect with other citizen scientists. The user can also download the light curve data to analyze it independently or save the star to their "favorites". The Discussion Board ("Talk"⁵) is a critical component of the Planet Hunters project. Here, the science team interacts with the public and experienced users establish collections of similar light curves (e.g., "Variables in a Hurry," "Definite Transits," "Weird Stars") and provide advice for new users. The integration of discussion into the workflow has been successful in encouraging greater participation than in previous Zooniverse projects; more than 60% of registered Planet Hunters participants visit "Talk," and more than 35% make comments.

2.1 Planet Hunters Detection Efficiency

As a first check, we visually inspected all user assessments made in the first month after the site was launched for the first 306 Kepler planet candidates announced by Borucki et al. (2010a). This essentially provided a "head count" or a rough estimate of how many transit events were being flagged by participants and it provided feedback that was considered by the web development team for upgrades to the site (e.g., streamlining the assessment questions and transit marking routines). Note that this is simply a tally of the fraction of transits that were marked; we are not calculating the percentage of planets detected. For example, if a sample of ten stars had one hundred transit events and 80 of them were marked by 50% of classifiers, then the percentage of detected transits would be 0.8*50 = 40%. The 306 Kepler planet candidates (Borucki et al. 2010a), exhibited 1371 transits with planet radii between 0.1 and $1 R_{JUP}$. Overall, we found that two thirds of the transits for candidates announced by Borucki et al. (2010a) were correctly flagged. Only 10% of transit boxes were spurious (i.e., did not obviously correspond to a transit event).

3 KEPLER PLANET HUNTERS CANDIDATES

We also visually inspected ~ 3500 transit flags marked by Planet Hunters in light curves where five or more people indicated that a transit had been found. We first eliminated the known false positives, typically grazing and eclipsing binaries (Batalha et al. 2010; Prsa et al. 2011; Rowe et al. 2010), and published Kepler candidates (Borucki et al. 2010a, 2011) from the set of light curves flagged by Planet Hunters. On our internal web site, the team searched the extracted light curves, ran periodogram analyses, modeled

⁵ http://talk.planethunters.org/

³ www.planethunters.org

⁴ www.zooniverse.org

light curves for prospective candidates and checked for correlated pixel brightness centroid shifts to try to eliminate additional false positives. After an extensive filtering process, we reduced the number of possible planet candidates down to a preliminary list of forty five.

We ranked these candidates and sent the "top ten" to our Kepler co-authors; they examined the light curves with their data verification pipeline and immediately found that six of the ten were unlikely to be planet candidates. KIC 11904734 has a V-shaped transit and very large radius, suggesting an eclipsing binary star system. KIC 8043052 and KIC 12009347 have secondary occultations that are also consistent with eclipsing binary systems. KIC 4913000 and KIC 9097892 showed changing transit depths from quarter to quarter. This can occur when a nearby star contributes an amount of flux that is quarter dependent, changing as the instrumental point spread function changes. A more complete pixel centroid analysis showed that the transit signals for KIC 4913000, KIC 8242434, and KIC 9097892 were offset from the star by 4-6 arcseconds. KIC 11820830 initially appeared to be a strong planet candidate, however stellar modeling indicated that the most likely interpretation for this star was that it was an eclipsing binary (EB) system with a large early type star as the primary and a M or K dwarf secondary. The six false positive candidates are listed in Table 1.

However, three candidates survived the Kepler data verification pipelines. One of these is a possible multi-planet candidate and we are now obtaining Doppler follow-up. The remaining two candidates are presented here. Each of these candidates had in fact been flagged in Q1 by the Kepler TPS as Threshold Crossing Events. However, for various reasons, these objects were not promoted to the status of a "Kepler Object of Interest," or KOI.

3.1 KIC 10905746

KIC 10905746 has a Kepler magnitude of 13.496 and g - r color of 0.949. The Kepler Input Catalog (Kepler Mission Team 2009) does not list $T_{\rm eff}$, log g , [Fe/H] or stellar radius for this star. The star was dropped from the Kepler target list after Q1 because variability characteristics (amplitude and frequency) indicated that the star could be a giant and was therefore less desirable for the exoplanet transit survey; planet transit signals are much shallower and more difficult to detect around stars with large radii. The photometry for this star shows low frequency variability, with a period of ~ 16 days and an amplitude of more than 2%, which could be caused by spots rotating on the surface of the star.

The Planet Hunters participants were able to look past the large scale structure in the light curve and they identified possible transit events with a depth of about 0.2% that repeated on \sim 10-day intervals in the Q1 data. The shape and depth of the light curve seemed consistent with a planet and we did not detect photocenter offsets in the pixel arrays in our initial screening, which would have indicated a blended background eclipsing binary system.

To better understand the host star, we obtained a spectrum of this star at Keck with resolution of $R \sim 55000$, using HIRES (Vogt et al. 1994) on 2011 April 12. A faint companion was observed at a separation of about 5" on the guide camera and the image rotator was used to ensure that

the light from the companion did not enter the slit. With the excellent seeing and the greater than one magnitude difference between KIC 10905746 and the companion star, the scattered light contamination would have been less than one part in a thousand. The spectrum had a signal-to-noise ratio of about 140 and we used the Spectroscopy Made Easy (SME) code (Valenti & Piskunov 1996; Valenti & Fischer 2005) to model the stellar parameters: $T_{\rm eff} = 4237 \pm 114 {\rm K}$, $\log g = 4.73 \pm 0.1$, $v \sin i = 1.1 \pm 1$ km s⁻¹, and [Fe/H] $= -0.23 \pm 0.1$. The surface gravity that we measure with our LTE spectroscopic analysis is consistent with a main sequence star, rather than an evolved giant. Figure 2 (left, top row) shows a wavelength segment that includes the Mg I B triplet lines from the Keck spectrum. The wings of these lines are sensitive gravity indicators. However, in this case, the star is cool with significant line blanketing, which suppresses the continuum and makes it difficult to model the line wings. We tested the hypothesis that this star was a giant by running a grid of synthetic models and fixing the gravity between log g of 2.0 - 3.5. The chi-squared fit for our models improved with decreasing surface gravity over this range, but all fits were significantly worse than our model with $\log g = 4.73$.

The CaII H & K lines provide additional support of main sequence status for this star. Late type main sequence stars often have significant emission in the spectral line cores as a result of dynamo-driven magnetic activity in the star, like the strong emission in the CaII H & K line cores, shown in Figure 2 for KIC 10905746. However, it is far less common for evolved stars to show emission unless the stars are rapidly rotating or members of close spectroscopic binary systems (Isaacson & Fischer 2010; Gizis et al. 2002; Gunn et al. 1998; Gray & Nagar 1985), and we see no evidence for either of these attributes in KIC 10905746. The combination of emission in the cores of the CaII H & K and pressure-broadened wings in the Mg I B lines, together with the spectroscopic $T_{\rm eff}$, suggests that the star has a spectral type of roughly M0V. The stellar parameters are summarized in Table 2.

Our Kepler co-authors found that the Kepler TPS algorithm had flagged the light curve for KIC 10905746 in Q1 with a Multiple Event Statistic (MES) of 9σ , greater than the 7.1 σ threshold. However, the fit failed to converge during the next stage of data verification. As a result, the star was dropped, the full pipeline analysis was never carried out until it was flagged by the Planet Hunters.

The Kepler time series photometry for Q1 is shown in the top panel of Figure 3 (after removing the large amplitude, low frequency variability). The bottom panel of Figure 3 shows the data folded at the prospective orbital period and the red curve is the best fit theoretical curve with a period of 9.8844 \pm 0.0087d, an orbital inclination of 88.42 degrees and an inferred planet radius of 2.65 \pm 0.67R $_{\oplus}$. Just above the transit curve, we show the photometry from the opposite phase, where a putative secondary occultation might be observed. The search for secondary occultations allowed for eccentric orbits that were consistent with the data and stellar parameters. The anti-transit data are folded at a phase of 0.5 since no eccentricity or secondary occultations were detected when modeling the light curves.

A Monte Carlo analysis (Jenkins et al. 2008) iterates between a family of evolutionary models in the Yale-Yonsei isochrones (Demarque et al. 2004; Yi, Demarque & Kim 2008), and the spectroscopic parameters and orbital parameters (orbital period, transit depth and duration) to provide self-consistent estimates for uncertainties and stellar parameters, including Z (total heavy element abundance), age, density, luminosity, mass and radius. For KIC 10905746, age is not listed in Table 2 since there was almost no constraint from the evolutionary tracks. Since the transit depth is a function of the ratio of the planet to star radius, an accurate assessment of the stellar radius is critical for deriving the planet radius. The characteristics of this planet candidate are summarized in Table 4.

Because we do not have an independent measurement of the mass of the transiting object, KIC10905746 is a planet candidates rather than a confirmed planet. Photometrically diluted background eclipsing binaries (BGEB) can have transit depths similar to planets. The depth of an eclipsing binary system will normally be 10% or more (depending on the ratio of the stellar radii and the impact parameter), but if the eclipsing binary light curve is blended with a brighter foreground star, the composite light curve will have a shallower depth during the eclipse and can masquerade as a transiting planet candidate. However, other signatures of the BGEB can sometimes be found in the light curve: unequal primary eclipse and secondary occultation or V-shaped light curves (Batalha et al. 2010). Three tests were carried out to search for a BGEB. First, the light curve was examined for deviations from a planet model (e.g., variations in the depths of alternating transits or evidence for secondary occultations). In Figure 3, the even and odd transits are indicated with plus symbols and asterisks respectively and show that the alternating transit events do not have significant variations in depth and are well-fit with a transiting planet model, which is overplotted as a solid line. The photometric data plotted just above the transit curve are phase-folded at the predicted time of secondary occultation for a BGEB and fit with a theoretical (green) line that solves for an occultation with zero depth. We note that the search for occultations does not assume zero eccentricity, however, zero eccentricity is used to generate the anti-transit phased plot. For many BGEB's some dimming would be observed. The lack of a detected occultation is a necessary, but still not exclusive condition for a planet origin of the transit event.

To place stronger limits on the presence of a blended BGEB, adaptive optics (AO) observations were obtained on 2011 June 23 UT using NIRC2 at Keck. The conditions were excellent with $\sim 0.5^{\prime\prime}$ seeing and very little cirrus. The spatial resolution of the K-band AO images is about 45 mas. Figure 4 (top panel) compares a K-band image of KIC 10905746 from 2MASS⁶ (left) with our diffraction-limited K-band AO images (right) with square root scaling for the brightness. The 2MASS image is unresolved, but reveals a faint source $\sim 4^{\prime\prime}_{\cdot}2$ east of KIC 10905746, identified as KIC 10905748. The high resolution K-band AO images cleanly resolves these two sources. Our ability to rule out other close companions depends on the brightness contrast of the stars in K-band and their angular separation. The 3σ magnitude differences for excluding other sources are listed in Table 3 for separations ranging from 0.25 out to 4.0. We also obtained J-band images to better characterize the neighboring source. The magnitude difference between KIC 10905746 and KIC 10905748 is $\Delta K = 1.42$ mags and $\Delta J = 1.38$ mags. These images did not reveal any additional prospective contaminating sources.

The file headers of the Kepler data contain information about the pixel centroid at the time of every photometric measurement. If the transit is occurring on the source, then the brightness of the star will decrease, but the image centroid position will be unchanged. However, if we are really observing a blended system with a background eclipsing binary that is offset from the source, then the image centroid will shift during the eclipse. Centroids for the pixel images in the Kepler data were examined for this astrometric motion. The pixel centroid analysis yielded a high SNR detection for KIC 10905746 and no sign of astrometric motion was detected beyond the error circle of beyond 0.08 pixels. While these results do not rule out a background binary close to KIC 10905746, they do eliminate the nearby star, KIC 10905748, which is 46σ away in the model fit, as the source of the transit.

3.2 KIC 6185331

The Planet Hunters identified a single transit event for KIC 6185331 in the Q1 data and one additional transit was found in the Q2 Kepler light curve. The Kepler team notes that the TPS code also identified this as a prospective candidate with a MES of about 10σ in Q1 and 20σ in Q2. However, the data verification pipeline did not trigger to process these curves.

According to the Kepler Input Catalog, KIC 6185331 has a Kepler magnitude of 15.64, g - r color of 0.556, stellar radius of 0.664 R_☉, $T_{\rm eff}$ = 5578, log g = 4.786, and [Fe/H] = 0.287. We obtained a spectrum of this star with SNR~ 30 using HIRES at Keck Observatory. Our spectral synthesis modeling with SME yields an effective temperature of 5615± 80K, consistent with the KIC value. However, our analysis yields a lower gravity of log g = 4.19 ±0.15. Comparing the Mg I B triplet lines (Figure 2) there is indeed less pressure broadening than for KIC 8242434, which had a log g of 4.608. We also derive a slightly less metal rich composition than the KIC, with [Fe/H] = +0.11±0.1 and we obtain a best fit model for the lines with $v \sin i = 0.5$ km s⁻¹. No emission is seen in the core of the CaII H & K lines (Figure 2), indicating that this sunlike star has low chromospheric activity.

Figure 5 shows the time series data (top) and the phasefolded data (bottom), modeled with a 49.76971d period using the Q1 - Q7 data. We carried out the Monte Carlo analysis described in §3.1 for KIC 10905746 with the Y2 isochrones, orbital parameters and the spectral synthesis results to obtain self-consistent stellar parameters (listed in Table 2). With the derived stellar radius of 1.27 R_{\odot} , the planet is modeled with a best fit radius of 8.05 R_{\oplus} . There is some evidence in the model fit for an eccentric orbit or stellar radius as large as 1.4 R_{\odot} . We did not detect a contaminating BGEB: alternating transit events have the same depth, no decrease in brightness is observed at the predicted occultation time, and the pixel centroid analysis yielded a clean result for a transit on KIC 6315331 without any detected astrometric motion. The 2MASS and AO images are shown in Figure 4 (bottom, left and right). Because this is the faintest of the stars (Kepler magnitude of 15.64), the AO

⁶ http://irsa.ipac.caltech.edu/applications/FinderChart

images can only rule out contaminating background stars within $\Delta M_V < 2.7$ magnitudes at separations larger than 0".5. The AO contrast sensitivities are listed in Table 3.

3.3 KIC 8242434

Planet Hunters identified a single transit event in the Q1 data for KIC 8242434. When the Q2 data were released, two additional transit events were identified that were separated by 44 days. In consultation with the Kepler team, we learned that the TPS had flagged this star with a MES of about 10σ . Because this was a single event, the data verification was not processed until Q2, and was not classified as a KOI.

The KIC lists a Kepler magnitude of 13.054 and g - r color of 0.937, $T_{\rm eff} = 4665$ K, log g = 4.176, a high metallicity of +0.437 and a stellar radius of 1.337 R_☉ for KIC 8242434. We analyzed a Keck HIRES spectrum with SNR of about 55 and derive a similar temperature, $T_{\rm eff} = 4757 \pm 60$ K. However, we find a higher surface gravity, log g = 4.608\pm0.1, consistent with a main sequence luminosity class. The wings of the Mg I B triplet lines (Figure 2) are broad and by eye are consistent with the higher surface gravity. Our analysis also yields a lower metallicity, [Fe/H] = 0.07 and $v \sin i = 0.4$ km s⁻¹. The CaII H & K lines (Figure 2) have emission in the line core; this emission would be typical for a low mass main sequence star, but less common for a subgiant. The stellar parameters are summarized in Table 2.

Figure 6 shows the time series and phase-folded Q1 - Q7 photometry for KIC 8242434. The light curve does not show evidence for a BGEB: the transit depth is constant for alternating transits and no dimming occurs at the predicted time of occultation in the phase-folded data just above the transit curve. The orbital period is modeled as 44.963888d. A Monte Carlo analysis was used to iterate to the self-consistent stellar parameters listed in Table 2 (again, there was not a good constraint for the stellar age). The stellar radius is estimated to be 0.719 $\rm R_{\odot}$, and together with the transit depth, this implies a planet radius of 2.32 $\rm R_{\oplus}$. The parameters for the planet candidate are summarized in Table 4.

The measured position of the transit source shows a statistically significant (5.7 sigma) 0.6 arcsec offset from KIC 8242434, indicating that the transit signal is likely due to a dim background binary. The source position is measured by taking robust weighted average of the observed transit source position in quarters 1-8, as determined by centroiding the difference between average in-transit and out-of-transit pixels (Bryson et al. 2011). Modeling indicates that this offset is not due to systemic centroid biases due, for example, to crowding. The K-band 2MASS image is shown in Figure 4 (middle, left) and the AO image (Figure 4, right) shows some unusually bright speckles within an arcsecond, with the most prominent one in the south-east. The AO images and pixel centroid analysis casts doubt on the planet interpretation and suggests the presence of a confusing background source; likely a BGEB.

3.4 KIC 11820830

KIC 11820830 exhibits significant oscillations, however, participants readily identified several transit events in the Q1 light curve. The Kepler TPS had also flagged this star with a MES of 46σ , the highest SNR threshold of any of the candidates presented in this paper. However, the light curve failed additional tests and was not processed by the data verification pipeline. Figure 7 shows the remarkable time series (top) and phase-folded (bottom) light curves for Q1 -Q7 observations of this star.

The Kepler Input Catalog lists stellar parameters for KIC 11820830, including Kepler magnitude of 12.087, g - r color of 0.198, stellar radius of 1.428 R_{\odot}, $T_{\rm eff}$ = 7007K, log g = 4.224 and [Fe/H] = -0.009. We obtained a spectrum of this star using HIRES on Keck with SNR 90. We carried out spectral synthesis modeling and derive spectroscopic properties of the star.

This is the brightest of the our initial Planet Hunters candidates, and normally it would have been possible to follow-up on this star with Doppler measurements to confirm the mass of the transiting object. However, our spectroscopic analysis revealed a high rotational velocity, $v \sin i = 52 \pm 5$ km s⁻¹ which significantly reduces the intrinsic radial velocity precision. Figure 2 shows the Keck wavelength segments for the Mg I B triplet and CaII H & K lines respectively, and the high rotational velocity is apparent from the broad stellar lines in these Figures. The broad spectral lines also reduce the precision of our derived spectral parameters. With this caveat, we report the results of our analysis: $T_{\rm eff} = 6300 \pm 250$ K, log g = 3.6 ±0.2, and [Fe/H] = +0.26 ±0.2.

Unfortunately, the self-consistent Monte Carlo analysis indicates that KIC 11820830 is likely to be an eclipsing binary system, with an early type primary star eclipsed by a K or M dwarf in an eccentric orbit. No astrometric motion was detected in the pixel centroid analysis and the AO images did not detect an additional source with a $\Delta M_V < 4$ magnitudes at separations of 0.25. The AO contrast sensitivities are summarized in Table 3.

4 DISCUSSION

The Planet Hunters website was launched to engage the public in front-line research by presenting light curve data from the Kepler Mission. This project joins a growing list of citizen science Zooniverse projects, and is the first to present time series data, rather than images. We debated whether the unique pattern recognition skills of the human brain would be able to compete with the efficient computer algorithms. However, we expected that citizen scientists might discover unexpected patterns in the data or unusual types of transits, which could then be used as feedback to further improve the Kepler transit search algorithms. Citizen scientists identified some unusual objects in the Galaxy Zoo program, and we expected that some unpredictable and unanticipated discoveries and correlations might also emerge from Planet Hunters. Automated algorithms and citizen science are complementary techniques and both are important to make the best use of the Kepler data.

An initial assessment was made of the performance and efficiency of the Planet Hunters participants by counting the number of transit events detected among the 306 candidates announced for Q1 data by Borucki et al. (2010a). We found that Planet Hunters flagged about two thirds of those transit events. The deeper transits were found more often than the shallow transits. In the first month after the launch of the Planet Hunters website, more than forty stars were flagged as possible planet transits that were not known false positives (grazing binaries or blended background eclipsing binaries) or published Kepler candidates. Because we felt it was important to preserve the integrity of the Kepler planet candidates, we contacted members of the Kepler team who provided important data verification for our top ten candidates. More than half of these were found to be false positives.

We present the first two planet candidates, discovered by Planet Hunters using Q1 data: KIC 10905746 and KIC 6315331, with orbital periods that range from 9.88 to 49.96 days and radii ranging from 2.32 to 8.0 R_{\oplus} . We have carried out a Monte Carlo analysis for a self-consistent set of stellar parameters and analyzed the pixel centroid's to check for astrometric motion. We also obtained adaptive optics (AO) observations to eliminate background eclipsing binaries (BGEBs) with separations wider than $\sim 0.5^{\circ}$ and $\Delta M_V < 5$ in the infrared K-band data. However, the pixel centroid analysis and AO observations cannot exclude eclipsing binaries that are are closer than 0.5' or those with wider separations that are more than about 5 magnitudes fainter than the tentative planet host stars. Because such systems could still produce the observed light curves, these two candidates are not confirmed planets.

We estimate false positive probabilities (FPP) for the two candidates presented here following the framework presented in Morton & Johnson (2011), which relies on Galactic structure and stellar population synthesis models. We consider two possible false positive scenarios: chance-alignment blended eclipsing binaries and hierarchical triple eclipsing systems, both of which can produce signals that mimic transiting planets. However, given that these transits are not V-shaped, we observe no secondary eclipse, and pixel offset calculations and AO observations indicate that any possibly blending systems can only reside within a fraction of an arcsecond of the target stars, we are able to put strong statistical constraints on the likelihood of false positive scenarios. Assuming an overall 20% occurrence rate for planets, a planet radius function $dN/dR \sim R^{-2}$, and the binary and multiple system properties according to Raghavan et al. (2010), as discussed in more detail in Morton and Johnson (2011), we derive an FPP of only 0.3% for KIC 10905746 and an FPP of 5.0% for KIC 6185331. The higher FPP for KIC 6185331 is set primarily by the fact that it has a deeper transit and thus is more susceptible to the hierarchical blend false positive scenario, which is not significantly constrained by the AO observations or centroid analysis.

An obvious question is why these candidates were not identified by the Kepler team. One motivation for the Planet Hunters project was that there might be odd cases that computer algorithms might miss, but that the human brain would adeptly identify. In fact, we learned that all of the planet candidates presented here had previously been flagged by the Transit Planet Search (TPS) algorithm. However, two of the candidates presented here had multi-quarter light curves that did not converge and the third candidate was dropped after Q1 because it was thought to be an evolved star. Therefore, these stars were not promoted to the status of a Kepler Object of Interest (KOI), which would have triggered extensive follow-up. It is not really surprising that a few candidates failed to converge in the analysis pipelines and remained behind to be gleaned by Planet Hunters. The discoveries presented in this paper show the challenges of field confusion for transiting planets, yet also shows that Citizen Scientists can make important contributions.

Planet Hunters is a novel and complementary technique to the Kepler Teams detection algorithms with different systematics and intrinsic biases than computer based algorithms. Algorithms are now being developed to process Planet Hunters classifications and assess the capabilities of individual volunteers based on light curves injected with synthetic short-period planet transits. Weightings will be assigned to individuals, and an iterative process will be used to converge on final classifications for each star. These algorithms will extract transit candidates automatically, and this analysis will be presented in a future paper.

ACKNOWLEDGEMENTS

The data presented in this paper are the result of the efforts of the Planet Hunters volunteers, without whom this work would not have been possible. The following list of people flagged transit events for the light curves discussed in this paper: Juan Camilo Arango Alvarez, Mary-Helen Armour, Ferdinand de Antoni, Frank Barnet, bhugh, Carolyn Bol, Les Bruffell, Dr. David M. Bundy, Troy Campbell, Elisabeth Chaghafi, Amirouche Chahour, Arunangshu Chakrabarty, Mathias Chapuis, Fabrice Cordary, Daniel, ClmentDoyen, Graham Dungworth, Michael Richard Eaton, David Evans, Raymond Ashley Evans, Evgeniy, Enrique Ferreyra, Marc Fiedler, Dave Fischer, Fin J. R. Fitz-Patrick, Dr Ed Foley, Lorenzo Fortunato, Sebastian Frehmel, Robert Gary Gagliano, Fabio Cesar Gozzo, Howard Hallmark, Dave Henderson, Inizan, irishcoffee, Thomas Lee Jacobs, Marta Kałużna, Bill Kandiliotis, Rafal Kurianowicz, Lukasz Kurzysz, Piotr Laczny, David M. Lindberg, Janet Lomas, Luis Miguel Moreira Calado Lopes, Mihael Lujanac, Lukasz, Cssia Solange Lyra, Jacek M, Riccardo Marzi, Karen McAuley, Tomasz Miller, Cedric MOULIS, Adrian Nicolae,Njaal,Michael W Novak, Osciboj, Kai Pietarinen, Anna Podjaska, Marc A. Powell (Omeganon), Gerry A. Prentice, John M. Rasor, Ren-Pierre BUIGUES, Andres Eloy Martinez Rojas, Rouz, Andrey Sapronov, Matt Schickele, Terrance B. Schmidt, David Smith, Paulina Sowick, Lubomír Stiak, Charles H Tidwell III, tuckdydes, v5anw, Joop Vanderheiden, VIATG, vovcik91, Sbastien Wertz, Bohdan Widla, Steven C Wooding, Charles Yule.

DF acknowledges funding support from Yale University and support from the NASA Supplemental Outreach Award, 10-OUTRCH.210-0001. DF thanks the Yale Keck TAC for telescope time used to obtain data for this paper. MES is supported by an NSF Astronomy and Astrophysics Postdoctoral Fellowship under award AST-100325. Support for the work of KS was provided by NASA through Einstein Postdoctoral Fellowship grant numbers PF9-00069, issued by the Chandra X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-03060. The Zooniverse is supported by The Leverhulme Trust. We gratefully acknowledge the dedication and achievements of Kepler Science Team and all those who contributed to the success of the

mission. We acknowledge use of public release data served by the NASA/IPAC/NExScI Star and Exoplanet Database, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We particularly thank the organizers (Charles Beichman, Dawn Gelino, Carolyn Brinkman) and lecturers (David Ciardi, Stephen Kane, Kaspar von Braun) at the July 2010 Sagan Summer Workshop for providing information and guidance that led to the inspiration for the Planet Hunters site. The Kepler public release data is primarily hosted by the Multi-mission Archive (MAST) at the Space Telescope Science Institute (STScI) operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G. This research has made use of NASA's Astrophysics Data System Bibliographic Services.

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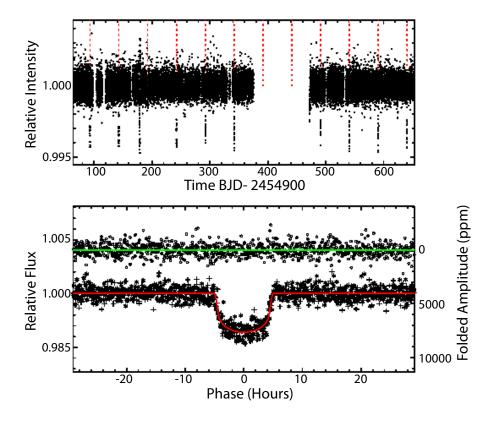


Figure 1. These slides from the Planet Hunters interface show the light curve for KOI 889.01 (top). Participants use a mouse-drag to identify prospective transit features (bottom).

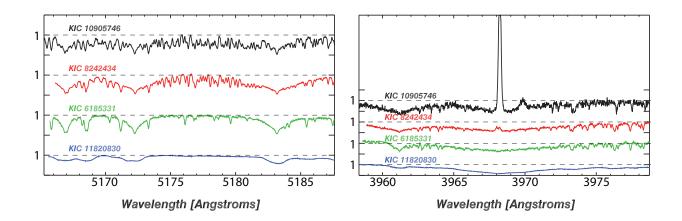


Figure 2. (left) The wings of the Mg B triplet lines are sensitive to pressure broadening, making these lines useful diagnostics of the surface gravity or luminosity class of stars. The spectra above were obtained at Keck and the stars are ordered from high to low surface gravity based on our spectral synthesis models. (right) Emission in the cores of the CaII H & K line is an activity indicator for main sequence stars. The spectra above show the Ca II K line for each of the planet candidate hosts presented here. The strong emission for KIC 10905746 is typical for a late-type main sequence star.

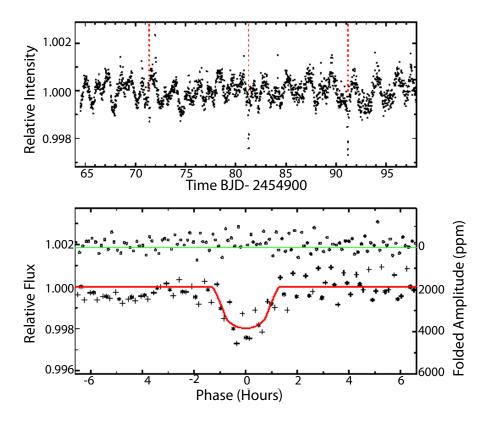


Figure 3. The top panel shows the time series data for KIC 10905746 between 2009 May 2 and 2009 June 15 after removing a large amplitude periodic signal. Planet Hunters flagged the three transit events indicated with a vertical dashed red line in the Q1 data. In the bottom panel, the light curve is phase-folded at the prospective orbital period P = 9.8846 days after removing the baseline variability. The fitted transit model is overplotted with a red curve. Just above the transit light curve, the anti-transit photometry is plotted and fit with a green curve showing zero depth for the occultation.

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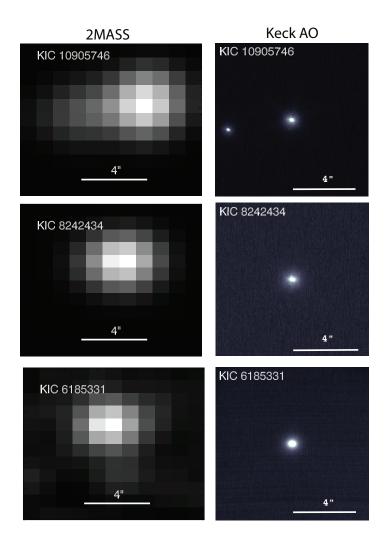


Figure 4. The 2MASS K band images (left) and AO images (right) for the two planet candidate hosts, KIC 10905746 and KIC 6185331 and for a star where a background eclipsing binary was found, KIC 8242434. The horizontal line indicates the image scale in arcseconds. North is up in these images and East is to the left. KIC 10905746 is shown in the top panel; the 2MASS image shows distortion from a nearby star at about 4 arcseconds due East, which is completely resolved by the AO K-band image (right). The middle panel shows 2MASS and AO images for KIC 8242434 and to the magnitude limits listed in Table 3, no additional sources are observed, however the photocenter was observed to shift during the prospective transit, indicating that a nearby backgroud eclipsing binary star producing the transit signal. The bottom panel shows images for KIC 6315331 with weaker limits on excluded background sources because of the intrinsic faintness of this star.

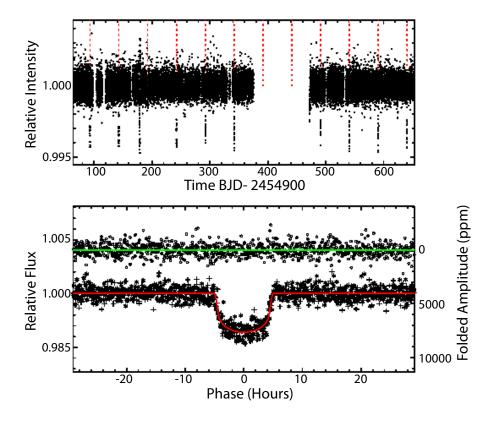


Figure 5. The time series data for KIC 6185331 (top) include Q1 - Q7 data. Planet Hunters flagged a single transit in the Q1 data and a one additional transit was seen in the Q2 data. The bottom panel shows the data folded at the prospective orbital period, 49.7700 days.

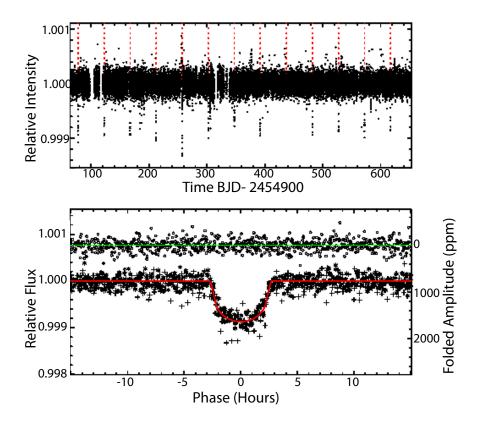


Figure 6. The time series data for KIC 8242434 (top) include photometry for Q1 - Q7, provided by the Kepler team. Planet Hunters flagged a single transit in the Q1 data and two additional transits were found in the Q2 data. The bottom panel shows the data folded at the prospective orbital period, 44.9634 days. Unfortunately, the pixel centroid check shows that this is llkely a background eclipsing binary system.

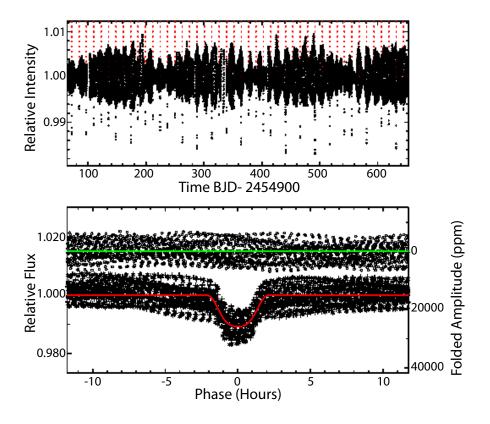


Figure 7. The time series data for KIC 11820830 (top) include Q1 - Q7 data. This star has a remarkably variable background However, Planet Hunters were able to see past that structure and flagged several transits in the Q1 data. The bottom panel shows the phase-folded data with the prospective orbital period, 12.7319 days. Unfortunately, the best model for this star suggests that the primary is an early type star with an eclipsing M or K dwarf companion

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 Table 1.
 False Positive Planet Candidates

Starname	Comments	
KIC 11904734 KIC 8043052 KIC 12009347 KIC 4913000 KIC 9097892 KIC 11820830	V-shaped transit and very large radius (EB) Secondary occultations (EB) Secondary occultations (EB) Astrometric motion in pixel centroids (BGEB) Astrometric motion in pixel centroids (BGEB) Eclipsing binary (based on model fits)	
KIC 11820830 KIC 8242434	Astrometric motion in pixel centroids (BC	

Parameter	10905746	6185331	8242434	11820830
Right Ascension	18 54 30.92	18 57 05.75	19 39 49.22	19 40 51.98
Declination	$48 \ 23 \ 27.6$	41 32 06.1	$44 \ 08 \ 59.3$	$50\ 05\ 03.58$
Kepler mag	13.49	15.64	13.05	12.09
g - r	0.949	0.556	0.937	0.198
$M_* [M_{\odot}]$	0.578(0.032)	1.027(0.042)	0.761(0.028)	2.25(0.3)
$R_* [R_\odot]$	0.548(0.026)	1.27(0.17)	0.719(0.031)	4.1 (0.3)
Z	0.0119(0.003)	0.0261 (0.0032)	0.0234(0.003)	. ,
Age [Gyr]	•••	8.7 (1.5)	•••	
$L_* [L_\odot]$	0.086(0.081)	1.02(0.03)	0.77(0.04)	2.25(0.3)
$\rho_* [\text{gcm}^-3]$	4.97 (0.54)	0.70(0.26)	2.9(0.38)	
$T_{\rm eff}$ [K]	4240 (112)	5619 (80)	4757 (60)	6300(250)
[Fe/H]	-0.23(0.1)	+0.11(0.15)	+0.07(0.08)	+0.26(0.2)
$v \sin i [\mathrm{km \ s^{-1}}]$	1.1(0.50)	0.5(0.50)	0.4(0.50)	52 (5)
logg	4.724(0.028)	4.239(0.098)	4.608(0.041)	3.6(0.2)

 Table 2.
 Stellar Parameters

Starname	025	05	10	20	40
KIC 10905746	3.7	5.6	7.8	8.6	8.6
KIC 6185331 KIC 8242434	$1.1 \\ 3.5$	$2.7 \\ 5.1$	$4.8 \\ 7.2$	$5.2 \\ 7.8$	$\begin{array}{c} 5.3 \\ 7.9 \end{array}$
KIC 11820830	4.2	5.7	7.2	7.6	7.6

Table 3. Δ K Magnitude AO Exclusion Limits

Parameter	10905746	6185331
T ₀ [BJD-2454900]	71.4045 (0.0102)	92.9877 (0.0028)
Orb. Per. [d]	9.8844 (0.0087)	49.76971 (0.00039)
Impact parameter, b	0.82(0.21)	0.642(0.142)
R_{PL}/R_*	0.0442 (0.0110)	0.0581 (0.0018)
$esin\omega$	0.08(0.42)	0.10 (0.32)
$ecos\omega$	0.00(0.43)	0.00(0.34)
R_{PL} [R $_{\oplus}$]	2.65(0.67)	8.05 (1.08)
Incl [deg]	88.42(0.42)	89.20 (0.21)
a/R_*	29.4 (1.1)	38.1 (8.4)
a [AU]	0.0751 (0.0014)	0.2672(0.0036)
T depth (ppm)	1881. (343.)	3633. (59.)

 Table 4.
 Characteristics of Planet Candidates