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The *Kepler* Follow-up Observation Program

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ABSTRACT

The *Kepler Mission* was launched on March 6, 2009 to perform a photometric survey of more than 100,000 dwarf stars to search for terrestrial-size planets with the transit technique. Follow-up observations of planetary candidates identified by detection of transit-like events are needed both for identification of astrophysical phenomena that mimic planetary transits and for characterization of the true planets and planetary systems found by *Kepler*. We have developed techniques and protocols for detection of false planetary transits and are currently conducting observations on 177 *Kepler* targets that have been selected for follow-up. A preliminary estimate indicates that between 24% and 62% of planetary candidates selected for follow-up will turn out to be true planets.

Subject headings: techniques: radial velocities, techniques: spectroscopic

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1. Introduction

Kepler, a NASA Discovery Mission designed to determine the frequency of terrestrial-size planets in and near the habitable zone of solar-like stars, was launched on March 6, 2009 and has been returning scientific data since early May 2009. The specific goals of the mission are:

- Determine the frequency of Earth-size and larger planets in or near the habitable zone of a wide variety of stars.

- Determine the distributions of planet sizes and orbital semi-major axes

- Estimate the frequency and orbital distribution of planets in multiple-star systems.

- Determine the distributions of semi-major axis, albedo, size, mass, and density of short-period planets giant planets.

- Identify additional members of each photometrically discovered planetary system using complementary techniques.

- Determine the association of stellar properties with planetary characteristics.

Kepler will survey more than 100,000 late-type dwarf stars in the solar neighborhood with visual magnitudes between 9 and 16 for a period of 3.5 years looking for transits of planets around those stars. Details of the *Kepler Mission*, the photometer and its operating modes are given in Borucki, et al. (2010a) and Koch, et al. (2010a).

While the *Kepler* photometer is capable of detecting transits of Earth-size planets around its target stars the photometric detections must be supplemented by follow-up observations with other facilities to identify transit-like signals from non-planetary sources and to accomplish goals of the mission beyond just detection of the planets. The *Kepler* Follow-up Observation Program (FOP) is designed to provide these supplemental observations.

2. Purpose of *Kepler* Follow-up Program

The detection of a transit-like signal in a *Kepler* target star is not sufficient evidence to confirm the presence of a planet orbiting the target star, nor would it be for any transiting planet survey. Brown (2003) distinguishes 12 combinations of giant planets and stars in eclipsing and transiting systems that can produce light curves mimicking a planet transiting a solitary primary star. Six of the combinations do not involve planets at all and four others

distort the transit light curve so that the size of the planet is indeterminate. In the case of *Kepler* where it is practical to detect transits of planets down to the size of Earth and below additional opportunities for confusion exist.

The principal causes of false positive or ambiguous planet size detections for *Kepler* are:

1. Background eclipsing binaries where a distant eclipsing star system's light is confused with and diluted by the light of the *Kepler* target star. The deep eclipse of the binary will appear as a shallow transit characteristic of a planet around the target star.

2. Eclipsing binaries in multiple-star systems where the multiple system is the *Kepler* target but the deep eclipse of the binary is diluted by the light of other stars in the system so as to appear as shallow as a planetary transit.

3. Grazing eclipses of binary stars that are *Kepler* target stars

4. Transits in a binary system consisting of a giant star and a main sequence star

5. Transits of background main sequence stars by giant planets that are diluted by the light of the *Kepler* target star so as to appear as shallow as transits of Earth-size planets

6. Transits of giant stars by giant planets that appear as shallow as Earth-size planets transiting main sequence stars.

In general light curve data alone cannot distinguish between these six configurations and the principle objective of the *Kepler* survey, Earth-size planets transiting main sequence stars. *Kepler* data is collected in a way that allows determination of the photo-center of light around the target star which can often identify causes 1 and 5 above (see sections 3.1 and 4.1 below). Careful spectroscopic and photometric follow-up observations of candidate transiting planets are needed to fully determine the source of a *Kepler* transit signal.

The *Kepler* follow-up observation program therefore has two purposes. First, the follow-up program must separate false positive transit indications from true planets to a high degree of reliability. Second, the follow-up program will characterize a representative sample of planets and planetary systems by determining the mass and orbit of the transiting planet and any other detectable, non-transiting planets.

3.   False Positive Elimination

3.1.   Elimination with *Kepler* data

False positive elimination for *Kepler* transit detections begins in the *Kepler* Pipeline (Jenkins, et al. 2010a) using only *Kepler* data. After transit-like signals are detected and matched against each other to find periodic series of transits, the series, now called Threshold Crossing Events (TCEs), are checked for adequate signal to noise ratio (SNR), regularity of period, transit depth, transit shape and consistency with Kepler's (the astronomer) laws of planetary motion. TCEs that pass these tests are subject to a preliminary photocenter motion analysis wherein the motion of the centroid of the light distribution in the photometer aperture, in and out of transit, is measured. Large centroid motions likely indicate that a nearby object, not the *Kepler* target, is the source of the transit signal. In these cases examination of the light curves from individual pixels in the photometer aperture usually identifies the background object. These steps will attack false positive causes 1 and 5 in section 2.

The full light curve of the target star, in and out of transit, is examined by a human to look for characteristic signs of an eclipsing binary star or other behavior unexpected of a transiting planet. A power spectrum of the light curve may be examined to determine if the target star is a giant or a dwarf as giants will display noise levels typically an order of magnitude higher than dwarfs (see, for example, the analysis of KOI-145 in Gilliland, et al. 2010). (The *Kepler* planetary target set is intended to exclude giants except in specific cases; see Batalha, et al. (2010b). However, some giants will inevitably have leaked in.) Examination of the light curve can also help detect grazing transits of stellar companions or giant planets which can be mistaken for transits of small planets. These steps will attack causes 2, 3 and 4 in section 2.

All of these pre-FOP steps are described more fully in the companion paper by Batalha, et al. (2010a). At the time of this writing these steps have, for the most part, been carried out manually. With the delivery of the next version of the *Kepler* Pipeline many of the steps will be automated.

3.2.   Elimination with Follow-up Observations

Planetary candidates that survive elimination on the basis of the *Kepler* data are sent for follow-up observation (see section 4 below) where moderate precision (~ 300 m/s), moderate SNR radial velocity (RV) measurements are used to detect and eliminate stellar mass

companions as the cause of the transit signal. Spectra for these measurements are usually taken at high resolution, as for high precision radial velocity work, but without enhancements such as exposure through an iodine cell that enable high RV precision. Imaging under good seeing conditions, active optic imaging and speckle imaging are used in combination with the previously obtained centroid motion analysis to determine if the *Kepler* target is the true source of the transit signal. Moderate precision, high SNR spectra may be used for line bisector analysis to detect multiple-star systems (see Torres, et al. 2004, and references therein). The moderate precision spectra are also used for classification of the target stars. These methods are generally the same as those discussed by Alonso, et al. (2004).

These follow-up observations will detect false positives due to eclipsing binary stars both in the background of the *Kepler* target and as the target star itself, either as a solitary binary or in a multiple-star system where a third light dilutes the transit. Planetary candidates surviving all of these observations and tests should have a high probability of being a true planet.

The current gold standard for extrasolar transiting planet confirmation is radial velocity determination of an orbit for the planet that is consistent with the timing and duration of the observed transits. Measurement of the planet's mass is also confirmatory. This sort of determination will be possible only for a fraction of the planets anticipated to be detected by *Kepler*, given the limitations of the sensitivity of the RV method and the resources available to *Kepler*. Giant planets around late type main sequence stars with orbital periods up to a few years and Earth mass planets in short period orbits around low mass stars will produce enough reflex motion in their parent stars to be measurable with current spectroscopic techniques. Some examples of this kind of confirmation for *Kepler* planet detections can be found in papers in this volume (Borucki, et al. 2010b; Koch, et al. 2010b; Dunham, et al. 2010; Latham, et al. 2010; Jenkins, et al. 2010b). The low mass planets in long period orbits expected to be detected by *Kepler* will not produce enough reflex motion to be seen by current instrumentation. Additionally, the bulk of *Kepler* planetary survey targets are fainter than about 13.5 visual magnitude making high precision radial velocity measurements prohibitively expensive or impossible. Confidence in most low mass planets found by *Kepler* will have to be based on the quality of the photometric data and elimination of false positive possibilities.

4.   Operation of Follow-up Program

As the results of the analyses of the *Kepler* data described in section 3.1 become available, the *Kepler* TCE Review Team (TCERT) convenes to review the results and select TCEs

that are likely to be true transiting planets. The selected TCEs are assigned *Kepler* Object of Interest numbers (KOIs) and the TCERT requests the FOP Observer Group (FOG) to begin false positive elimination on the KOIs. These requests include a statement of priority and a discussion of the analytical results that led to the selection of the TCEs and KOIs.

When requests are received from the TCERT the FOG reviews the priorities and analyses and begins observations of the KOIs following a protocol for false positive elimination. As data and results of the follow-up observations accumulate, the FOG discusses the status of each KOI under active observation to monitor the course of the observations. When work is completed and the FOG has decided the disposition of the KOI the results are passed back to the TCERT and the *Kepler* Science Analysis System (KSAS, described below).

The TCERT then reviews the results of false positive elimination and may ask the FOG to perform more observations on selected KOIs to further characterize a planet or planetary system.

4.1. Follow-up Protocol

The protocol for elimination of false positives consists of a series of observations with 1-3 meter class telescopes with good spectroscopic or high spatial resolution capability.

1. Begin with a reconnaissance spectrum taken at moderate precision and with moderate signal to noise ratio to provide radial velocity precision of ~ 300 m/s. This spectrum will verify and improve stellar parameters from the *Kepler Input Catalog* and determine the star's rotation velocity. Fast rotating stars ($v \sin i \geq 15$ km/s) and hot stars, early F and earlier, that show nearly featureless spectra are more difficult for high precision RV measurements and may be given low priority for characterization studies. Double-lined spectroscopic binaries that escaped pre-FOP detection due to grazing eclipses shallow enough to be mistaken for planetary transits may be detected at this point. This reconnaissance spectrum is also the first point in the RV time series needed to detect stellar mass companions. This step attacks false positive causes 3 and 6 described in section 2.

2. Obtain images of the field around the KOI using active optics, speckle imaging and conventional imaging to search for background objects that might be the source of the transit signal. Out-of-transit images provide the light distribution in the *Kepler* photometric aperture which allows detailed interpretation of the centroid motion analysis described in section 3.1. This analysis can often distinguish if the KOI is the source

of the signal. Latham, et al. (2010), Dunham, et al. (2010), Koch, et al. (2010b) and Jenkins, et al. (2010b) give examples of this analysis.

In-transit images, though harder to obtain due to observation scheduling difficulties, will occasionally be useful. For large transit signals, $\sim 1\%$, in-transit photometry can provide a definitive indication of which object in the aperture is producing the transit signal by observing which object dims during transit. For small signals, $\sim 0.01\%$ as expected for Earth-size planets, where centroid motion analysis may be too insensitive for definite determination of the signal source, in-transit photometry can provide falsification of background objects as the signal source by showing that any observed background object variations are too small to provide the transit signal (after Deeg, et al. 2010).

This step attacks causes 1 and 5 in section 2.

3. If the KOI is still of interest, continue moderate precision RV measurements. Stellar mass companions responsible for the transit signal will reveal themselves by large velocity variations consistent with an orbit commensurate with the transit light curve. This step attacks causes 3 and 4 in section 2.

4. Obtain a short time series of high SNR, moderate resolution spectra for line bisector analysis to detect KOIs which are multiple-stars where the transit signal is diluted by non-transited components of the system. This step attacks cause 2 in section 2.

This protocol also detects dilution of transits of true giant planets and can allow for correction of the dilution for proper measurement of planetary diameter.

KOIs determined to be background eclipsing binary stars will generally be eliminated from further follow-up observation. KOIs in which the target star is found to be an eclipsing binary may be removed from further observations if RV techniques cannot yield a planet confirmation. However, eclipsing binary systems are inherently interesting for a transiting planet search since the planetary plane is likely to be close to the binary plane. The TCERT may ask members of the *Kepler* Science Team to use other methods, such as transit timing variation, to search for planets around these stars.

4.2. Further characterization

After the FOP has reported to the TCERT that a KOI is likely to be a planet the TCERT may request, as mentioned above, that further characterization of the KOI be done. These requests are expected to be mainly for determination of planetary orbits and masses or for

precise measurements of stellar and planetary parameters, including planetary atmosphere temperature and composition. RV searches for additional, non-transiting planets may also be made. Methods employed include:

- High precision RV measurements (1-10 m/s) for orbit and mass determination and for searches for non-transiting planets. Measurements of the Rossiter-McLaughlin effect (Rossiter 1924; McLaughlin 1924; Kopal 1990) may be made, especially for stars with higher rotation rates for which RV is more difficult and RM is more sensitive. We have currently obtained RM data for one planet, Kepler-8b (Jenkins, et al. 2010b).

- Observation of secondary eclipses with the Spitzer Space Telescope to measure temperatures in the planetary atmosphere and to determine atmospheric composition.

4.3. Planet Confirmation

The *Kepler* team is currently working to develop and validate methods other than spectroscopic orbit determination for confirmation of transiting planets. Orbit determination is excessively expensive or impossible for the majority of planets expected to be detected by *Kepler*. Therefore, analysis of *Kepler* photometry combined with follow-up observations using moderate precision spectroscopy and high spatial resolution imaging, as described in section 4.1, or other methods that may be developed must be used alone to eliminate false positives, leaving a statistically reliable, but not perfect, set of planet detections. The standard method of spectroscopic orbit determination and Rossiter-McLaughlin detection are being used on the brighter *Kepler* targets harboring giant planets and low mass planets in short period orbits around low mass stars to determine the reliability of planets surviving the protocol of section 4.1.

We expect that *Kepler*'s extraordinary photometric precision, which allows detection of the odd-even effect in binary star eclipses, transit shapes that are inconsistent with planets and secondary occultations of actual transiting planets, can be combined with centroid motion analysis and follow-up spectroscopy to achieve the required degree of false positive rejection.

4.4. Resources

The follow-up program has a team of 16 observers and 5 other astronomers who dedicate at least part of their time to *Kepler* follow-up observations. The instrument facilities available

are shown in Table 1. In the 2009 observing season from June through November 13 nights of Keck time and more than 100 nights on other telescopes were used for *Kepler* follow-up observations.

5. Current Results

At the end of the 2009 observing season 177 Kepler targets have been identified as KOIs from commissioning (Q0) and quarter 1 (Q1) data sets and sent to the FOP for follow-up observation (see Batalha, et al. 2010a,b, for a description of these data). These 177 KOIs were selected from the Kepler planetary targets brighter than 15th Kepler magnitude and have been classified as shown in Table 2. This table is intended only to present the current status of Kepler follow-up observation and is not suitable for drawing statistical inferences. Obviously interesting numbers like completeness estimates for planet detection cannot yet be sensibly derived. Final versions, optimized for actual flight data, of the algorithms for transit detection, background eclipsing binary elimination and other procedures described in section 3.1 were not in place when these KOIs were selected. Indeed some steps of the selection were performed by human examination of the light curves and the number of background eclipsing binaries reflects early, inefficient versions of pre-FOP elimination. When improved versions of the algorithms are applied to the Q0 and Q1 data new KOIs may appear which will be followed up in future observing seasons. Sensible preliminary estimates of survey completeness and other statistics should begin to be available after the end of the 2010 observing season when our KOI selection methods are better understood and more KOIs currently under reconnaissance are resolved.

A preliminary estimate of the fraction of planets expected in the KOIs sent for follow-up observation is possible. A well studied set of 70 transit detections from planetary targets brighter than 14th magnitude have been subject to our current best versions of detection validation and background eclipsing binary elimination as described in section 3.1. Table 3 presents the state of follow-up observations for these 70 targets. Seventy percent of the initially interesting transit detections were found to be false positive in the pre-FOP vetting process. Of the 21 KOIs left for FOP follow-up, at least 24% are good planets. All 8 of the KOIs not yet rejected nor confirmed as planets could prove to be good planets, providing a first estimate of between 24 and 60% good planets in KOIs sent for follow-up observation. Small number statistics and incomplete analysis of the 8 KOIs currently prevent a better estimate.

We gratefully acknowledge the outstanding work of the enormous number of people on

the *Kepler* team who have contributed to the success of the mission, and without whom the Follow-up Program would have nothing to follow.

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Facilities: The Kepler Mission

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Table 1. Follow-up Resources

Telescope	Instrument	Institution	Location
Tillinghast reflector	TRES Spectrograph	CfA	Arizona
Shane telescope	Hamilton Spectrograph	Lick observatory	California
Nordic Optical Telescope	FIES Spectrograph		Canary Islands
Keck Telescope	HIRES Spectrograph	NASA	Hawaii
Palomar 5m Hale Telescope	PHARO/NGS AO camera	Caltech/JPL	California
WIYN Telescope	Speckle Camera	KPNO	Arizona
KPNO 2.1m Telescope	Gcam Spectrograph	KPNO	Arizona
KPNO 4m Telescope	RCSpec	KPNO	Arizona
Hobby Eberly Telescope	High Resolution Spectrograph		Texas
Harlan J. Smith Telescope	Tull Coude Spectrograph	McDonald Observatory	Texas
MMT	ARIES AO system	SAO/Univ. Arizona	Arizona
1.1-m Hall	NASA42 CCD Camera	Lowell Observatory	Arizona
1.8-m Perkins	PRISM CCD Camera	Lowell Observatory	Arizona
William Herschel Telescope	HARPS NEF spectrometer (when completed)		Canary Islands
Spitzer Space Telescope	IRAC camera (warm)	NASA	Earth trailing orbit
Hubble Space Telescope		NASA	low Earth orbit

Table 2. Current Status of Observations

Type	Number	
Total KOIs	177	From targets $m_{kepler} \leq 15$ in quarters 0 and 1
Planet	5	Good rv orbit matches light curve.
Possible planet	52	Radial velocity variation is small enough for a planetary mass companion.
Recon	65	Still under reconnaissance. No type assigned.
Double lined spectrum	5	
Stellar companion	8	RV variations indicate a stellar mass companion.
Triple system	1	Transit source is in a triple (or greater) system.
Background eclipsing binary	11	
Fast rotator	13	Star is rotating too fast for very precise velocities.
Withdrawn	14	Withdrawn by TCERT after re-examination of light curve
Unsuitable	3	Featureless spectrum unsuitable for RV work or no star apparent at target location

Table 3. False Positive Rejection Statistics

Type	Number	Fraction
Number of targets in well studied sample (see text)	70	
Rejected by photometric appearance or centroid motion	49	70%
KOIs left after pre-follow-up vetting	21	
Planet	5	24%
Not yet rejected nor confirmed as planets	8	38%
Rejected by FOP observation	7	33%
Dropped due to confusion with nearby stars	1	5%