Transiting Planets
Proceedings IAU Symposium No. IAUS253, 2008
Frédéric Pont, Dimitar Sasselov & Matthews Holman, eds.

doi:10.1017/S1743921308026513

KEPLER: Search for Earth-Size Planets in the Habitable Zone

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Abstract. The *Kepler Mission* is a space-based mission whose primary goal is to determine the frequency of Earth-size and larger planets in the habitable zone of solar-like stars. The mission will monitor more than 100,000 stars for patterns of transits with a differential photometric precision of 20 ppm at V = 12 for a 6.5 hour transit. It will also provide asteroseismic results on several thousand dwarf stars. It is specifically designed to continuously observe a single field of view of greater than 100 square degrees for 3.5 or more years.

This paper provides a short overview of the mission, a brief history of the mission development, expected results, new investigations by the recently chosen Participating Scientists, and the plans for the Guest Observer and Astrophysical Data Programs.

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1. Introduction

Over 250 exoplanets have been detected as of the time of this symposium (Marcy 2007). Most of these are gas giants, but super earths in short period orbits are now being found (Rivera *et al.* 2005, Baglin, this conference, and Mayor personal communication). However, the next step in the exploration of planetary systems is to find habitable planets, that is, those in the habitable zone (HZ) (Kasting *et al.* 1993) where liquid water can exist on their surfaces, and with a size and density such that they can have a life-sustaining atmosphere, that is, from about 0.8 to 2 $R_\oplus$, if one assumes a terrestrial density, from about 0.5 to 10 $M_\oplus$.

Finding extrasolar planets is extremely challenging and was not accomplished until 1995 when Mayor & Queloz, (1995) detected the first jovian-mass planet around normal stars. However, by making the observations from a space-based platform and using the transit method proposed by Borucki and Summers (1984), Earth-size planets, including those in the HZ, should be detected in substantial numbers. To win acceptance for a transit mission required: 1) evidence that the variability of the Sun and presumably most stars similar to the Sun on the time scale of a transit is substantially smaller in amplitude than that of a Sun-Earth transit analog, 2) proven detectors and associated electronics with noise levels sufficiently low that transit amplitudes expected from Earth-size transits over solar like stars exists (Robinson *et al.* 1995), 3) automated photometry of tens of thousands of stars could be done (Borucki *et al.* 2001), 4) to demonstrate that a space-based photometer with all the known forms of realistic noise has a combined differential photometric precision ∼20 ppm, one-sigma on the time scale of a transit (Koch *et al.* 2000), and that the mission requirements could be met with an acceptable budget and schedule. The proof that a spaceborne transit mission could successfully find Earth-size planets and could meet budget and schedule constraints required nearly ten years and five separate proposals before the Kepler Mission was selected for development in 2001.

In the following sections a brief history of the Kepler Mission is presented as well the most recent developments including the Participating Scientist Program (PSP) and the asteroseismology program. Section 2 is a short overview of Mission parameters. A more comprehensive discussion of the technical aspects of the Mission can be found in the earlier papers (Koch *et al.* 2006, Borucki *et al.* 2007).

2. Mission Overview

The Mission's top level scientific goals are to:

(*a*) Determine the frequency of terrestrial and larger planets in or near the habitable zone of a wide variety of spectral types of stars;

(*b*) Determine the distributions of sizes and orbital semi-major axes of these planets;

(*c*) Estimate the frequency of planets and orbital distribution of planets in multiple-stellar systems;

(*d*) Determine the distributions of semi-major axis, albedo, size, mass and density of short-period giant planets;

(*e*) Identify additional members of each photometrically discovered planetary system using complementary techniques; and,

(*f*) Determine the properties of those stars that harbor planetary systems.

To achieve these goals, three fundamental design requirements were established: the photometric precision, the mission life time and the number of stars observed.

(*a*) The photometric requirement is to detect individual Earth-size ($R = 1.0\,R_\oplus$) transits of 6.5 hrs (half of a central transit duration for a planet at 1 AU of a twelfth magnitude solar-like star with an SNR of greater than or equal to four, when all sources of noise (stellar variability, shot, and instrument) are included.

(*b*) A periodic sequence of at least three transits is required. Therefore the mission must last three or more years to detect planets in the HZ of a solar-like star.

(*c*) Finally, the photometer is required to observe enough solar-like stars to produce a statistically meaningful result. Hence, the aperture size, field of view and location on the sky have been chosen to provide at least 100,000 dwarf stars sufficiently bright to show detectable transits.

The photometer design is based upon a classical Schmidt telescope with a 95 cm diameter aperture and more than one-hundred square degree field of view (FOV). 42 CCDs with 95 million pixels are used to continuously monitor the star field.

The position of the field of view on the sky is in the Cygnus-Lyra region centered on $RA = 19^h\,22^m\,40^s$, Declination $= 44^\circ\,30'$, just above the galactic plane and looking down the Orion arm of the Galaxy. This provides a rich field of stars similar to those in our local neighborhood that is continuously viewable throughout the year as the spacecraft drifts away from the Earth on its orbit around the Sun. The combination of shot noise and instrument noise limits the magnitude of usable stars to about V = 15-16 for F-, G-and K-dwarfs and about V = 16.5 for M-dwarfs.

The single FOV will be viewed for the entire mission including any extended mission life. To keep the fixed-solar array pointed toward the Sun and the focal-plane radiator pointed to deep space, the photometer-spacecraft must be rotated 90° about the optical axis every 93 days. Two measurement cadences are available; 1 minute cadence for up to 512 targets and a 30 minute cadence available for up to 170,000 stars.

3. Brief history of the Kepler Mission

The Kepler Mission developed over several decades as a way of answering the question: How frequent are other Earths in our galaxy? In particular, what is the frequency of Earth-size planets in the HZ of solar-like stars? In the last half of the twentieth century, the astrometric and interferometric approaches to finding exoplanets were the favored methods. The surprising discovery by Wolszczan (1994) based on timing of radio pulses from pulsars showed that a wider range of approaches should be considered. A paper by Rosenblatt (1971) provided a quantitative discussion of another alternative method; searching for patterns of transits to get size and orbital period. To be successful, all three approaches depend upon adapting new technology; the underlying principles are well understood.

To examine the technology needed to accomplish transit detection of exoplanets, NASA Ames Research Center (ARC) sponsored workshops on high precision photometry in 1984 (Proceedings of the Workshop on Improvements to Photometry, 1984) and jointly sponsored by ARC and the National Bureau of Standards (now NIST) at Gaithersburg, Maryland in 1987 (Second Workshop on Improvements to Photometry, 1988).

To further develop this approach NASA HQ funded the development and testing of proof-of-concept multichannel photometers based on silicon photo diodes. Tests conducted at the NBS and at Ames showed that the diodes had very high precision as expected, but that to reduce their thermal noise, they would need to be cooled to near liquid nitrogen temperatures. Two cooled multichannel photometers were built; the latter was based on an optical fiber feed to the cooled diodes. Erratic transmission of the multimode fibers doomed the latter (Borucki *et al.* 1987, 1988).

In 1992, NASA HQ proposed a new line of missions to address questions about the Solar System and that would also consider the search for exoplanets. Proposals for concept studies were invited and discussed at a workshop at San Juan Capistrano, CA. The proposals were for complete missions: science, technical, engineering, management, cost, and schedule were to be addressed. For this opportunity, a team was organized to propose a transit search for terrestrial planets. The proposed mission was called 'FRESIP' (FRequency of Earth-Size Inner Planets) to describe its goal.

The review panel found that the science value was very high and would have supported the concept had there been proof that detectors existed with sufficient precision and the requisite low noise to find Earth-size planets.

Although the proposal was rejected, members of the team and the science community urged continuation of the ideas and in particular, stressed the wide variety of astrophysics that could be accomplished by observing thousands of stars continuously for a period of years. To explicitly investigate the astrophysics that could be accomplished, a workshop (Astrophysical Science with a Space borne Photometric Telescope, 1984) was held at the SETI Institute in Mountain View, CA. Promising areas of investigations included: solar and stellar physics; including star spots, activity cycle, oscillation, rotation rates, and flares, 2) stellar variability including cataclysmic variables, RR Lyra and δ-Scuti stars, and 3) extragalactic objects such as quasars and active galactic nuclei, and 4) acoustic

https://doi.org/10.1017/S1743921308026513 Published online by Cambridge University Press

oscillations to investigate the interior of stars and determine their mass, age, and helium abundance.

In 1994, the first flight opportunity for a Discovery-Class mission was announced. FRESIP proposed a 0.95 meter aperture photometer to be placed in a Lagrange orbit. CCD detectors were substituted for the silicon detectors because of their capability of tracking many targets simultaneously and their ability to accept many different target patterns. The review panel considered the FRESIP photometer to be a telescope similar to the Hubble Space Telescope (HST) and thus far too expensive to qualify as a Discovery-class mission. The proposal was rejected.

Lab tests to prove that CCD detectors were suitable were funded by small grants from NASA HQ and ARC. The first paper presenting the results of lab tests demonstrating the CCD detectors had the requisite precision and low noise to detect transit patterns of Earth-size transits was published in 1995 (Robinson *et al.* 1995). The experiment was carried out in the basement of Lick Observatory and used an old 512×512 Reticon front-side illuminated CCD. For many of the simulated stars a precision of 5×10^{-6} was achieved. Back-side illuminated CCDs, where the light does not pass through the wire traces on its way to the active silicon were expected to have even higher precision. An accidental spilling of liquid nitrogen during the lab tests did not cause loss of precision because the records of centroid movement allowed the motions to be regressed out. In fact it was the mathematical identification and removal of the systematic noise that was the break through step that allowed the intrinsic precision of these detectors to be recognized.

In 1996, the second opportunity to propose for a flight mission was announced. Studies showed that mission costs could be reduced if photometer was placed in a solar orbit rather than a Lagrange orbit because of the reduction of the space propulsion system needed to stay in a Lagrange orbit. The mission name was changed from FRESIP to "Kepler" to honor the German astronomer who developed the laws of planetary motion and the principle needed to calculate optical prescriptions. The mission cost was estimated in three different ways to show that the mission cost could be accomplished for the available budget. The proposal was rejected because no one had every demonstrated that the simultaneous, automated photometry of thousands of stars could be done. The review panel recommended that we build such a photometer to demonstrate the methods to be used. Funding was granted for such a demonstration from both NASA HQ and ARC.

In 1997, the photometer was designed and built. Arrangements were made at Lick Observatory to refurbish the Crocker Dome and to install a radio link between the dome and a receiving station at Ames. Software was written to control the dome and photometer and to analyze the data.

In early 1998, data was being received and analyzed on the simultaneous observations of 6,000 stars in a single field-of-view. Papers describing the results were published in 1999 and 2001 (Borucki *et al.* 1999, 2001). Later that year, the third opportunity to propose for a Discover-class Mission was announced. The review panel acknowledged that science was excellent; that the detectors could provide the necessary performance, and that automated photometry could be done on thousands of stars simultaneously. The proposal was rejected because there was no proof that a photometer with the precision required to find Earth-size planets could be developed that would operate satisfactorily on orbit with the types of noise encountered for such operation.

A proposal was written to build a laboratory demonstration that would incorporate all expected noise sources and impose Earth-size transits on a simulated, but realistic star field.

In 1999, the Kepler test bed was designed, built, and tested (Koch *et al.* 2000). The results were satisfactory and a report was written and communicated to the review panel chartered by HQ to verify the test performance.

In 2000, the fourth opportunity to propose for a Discovery-class mission was announced and Kepler proposed for the fifth time. Kepler was one of three proposals selected from a total of 26 that was allowed to compete by writing a Concept Study Report and demonstrating readiness to proceed.

In December of 2001, Kepler was selected as Discovery Mission #10.

During the years prior to selection, many events helped get the Mission concept accepted. Two major events were the discovery of extrasolar planets by Michel Mayor's team (Mayor & Queloz 1995) and Geoff Marcy's team (Marcy & Butler 1996) and success by several ground based transit search groups (Charbonneau *et al.* 2000). Once the radial velocity technique had convincingly demonstrated that many exoplanets existed and NASA HQ recognized that the transit technique was proven and the technology existed that could find Earth-size planets, both the development of the Kepler Mission and a vigorous ground based efforts were funded. In particular, the many years that the Kepler team devoted to convincing the science community, the technical review panels, and NASA HQ officials, helped promote the funding of ground-based transit surveys that are now so successful in finding and characterizing exoplanets. In turn the success of both the radial velocity and transit approaches helped the Kepler Mission to compete against the many excellent proposals received at every AO for a Discovery-class mission.

4. Recent Developments

The spacecraft and photometer have now been integrated. See Figures 1,2 and 3. Final testing is underway. Based on the current schedule, the spacecraft/photometer will be shipped to Cape Kennedy in mid December 2008 for launch on February 15, 2009. Commissioning will finish in March and science operations will begin immediately thereafter. Prior to shipment to the launch site, a plaque with the names of the individuals who have contributed directly to the Mission will be attached. A DVD containing the names of public who have submitted a short write up about their response to the Mission will also be carried.

5. Expected Results

The expected results are based on calculations that use the Kepler Science Merit Function (MF). This algorithm considers instrument-, mission-, and stellar parameters. The stellar parameters include mass, size, and number for the stellar distribution in the FOV as a function of apparent magnitude. The mission and instrument design parameters include the mission duration, the size of the FOV, duty cycle, and instrument-, jitter-, and shot noise for each magnitude. Characteristics of the stellar noise introduced by stellar variability are derived from the measured variability of the Sun.

The number of detected planets was estimated by first calculating the number of transits per star observed during the mission as a function of stellar type and planetary semi-major axis. Next, the detection probability was calculated for all magnitudes, spectral types and planet sizes using an adaptive, wavelet-based matched filter. To avoid false positive events introduced by statistical fluctuations caused by $\sim 10^{12}$ tests that must be conducted, the detection threshold was set at 7.1σ. Finally, the number of planets of each size detected was determined by multiplying the detection rate for each case by the

Figure 1. Spacecraft being prepared for the instrument attachment.

Figure 2. Photometer being mated to the spacecraft.

number of stars that have a planet at the correct geometrical alignment and that exhibit a minimum of three transits.

Because the number of planets expected to be detected depends on the number and characteristics of those assumed for the model calculation, the values shown in Figures 4 and 5 are for illustrative purposes only! The sole purpose of the Kepler Mission is to determine these quantities. For these calculations it was assumed that one terrestrial-size planet was in the habitable zone (HZ) of each star and Earth-size planets were at those locations where giant planets are commonly found: 0.05, 0.1, 0.2, 0.4, 0.6, 0.8. 1.0, 12., & 1.5 AU. When the position of the HZ is near any of the latter positions, the model assumes that the probability of a planet at that position is zero. To illustrate the capability of the instrument to rule out a large range of planet diameters, the left-hand curves considers four situations (shown in color): all planets in the HZ are the same size as Mars (result shown in blue), all planets in the HZ are exactly Earth-size (aqua + blue), all planets are 1.3 times the diameter of Earth (yellow + aqua + blue), and all planets in HZ are 2 times the diameter of Earth (sum of all four colors).

Thus if all planets in the HZ are actually the size of Mars and none are detected, then most or all of the observed stars can not have a planet the size of Mars or larger because the instrument has the capability of finding such planets. Since six detections are expected, the null result is significant. For the hypothesis that all target stars have an Earth-size planet in the HZ, the expected result is 80 detections and a null result implies that all or most stars do not have planets Earth-size or larger in their HZ.

Figure 5 shows that many thousands of Earth-size planets should be detected in inner orbits if such planets are common. Reducing the expected number of such planets by 10 or 100 provides a more likely estimate.

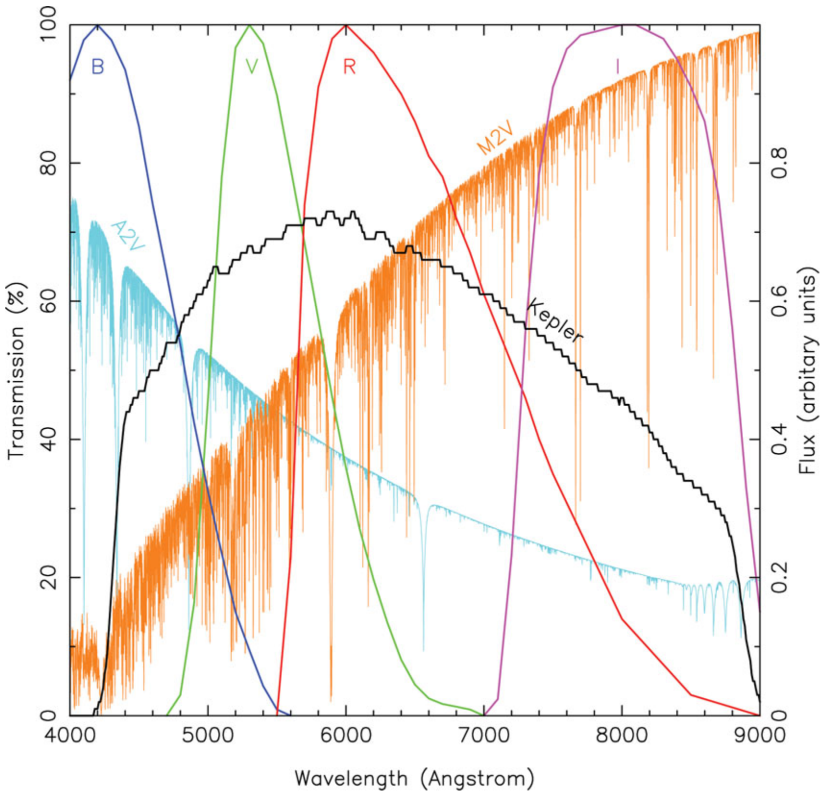

Figure 3. Instrument response vs. wavelength superimposed on the fluxes for early and late dwarf stars. The stars have the same V magnitude.

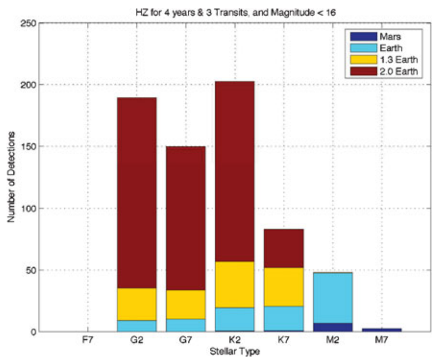

Figure 4. Expected number of detections based on the instrument capability, characterization of the Kepler FOV, and the assumption of one terrestrial planet in each HZ.

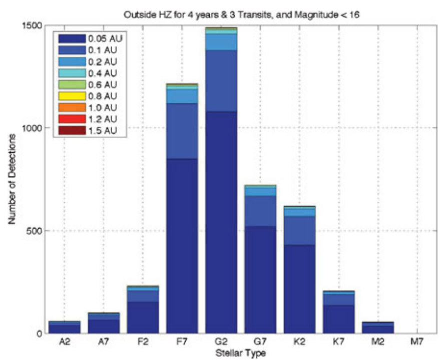

Figure 5. Expected number of detections for Earth-size planets distributed over a range of semi-major axes.

These calculations show that several hundred terrestrial planets should be detected in the HZ if they are common. A null result would mean Earths in the HZ are rare in our galaxy. Similarly several thousand Earth-size planets should be detected that are not in the HZ. The numerical results obtained from the Kepler measurements will provide the first estimates of planet size, orbital distribution, and association with stellar characteristics.

6. Additional Planned Analyses

In addition to using the data to search for sequences of transits and reflected light from (not necessarily transiting) close-in giant planets, the Kepler data will also be used for: obtaining parallax measurements, thereby obtaining the stellar size from measurements of the luminosity and distance; determining stellar rotation rates; and performing asteroseismic analysis.

6.1. *Asteroseismic Program*

Asteroseismic analysis will be performed by the Kepler Asteroseismic Science Consortium (KASC) to measure p-mode oscillations (Brown and Gilliland, 1994) of stars in the FOV brighter than about V = 11.5 to yield the mass, radius, density and age of those stars (Christensen-Dalsgaard *et al.* 2008).

Stars showing oscillations similar to those observed in the Sun are particularly promising targets for asteroseismology, owing to the large number of generally well-identified modes that can be observed. Such oscillations occur in stars across the cool side of the HR diagram, with oscillation periods of minutes to hours and increasing amplitudes and periods for increasing luminosity. The extensive experience from analyses of solar oscillations can be applied in the analysis of data for these stars. The solar-like oscillations are characterized by a great deal of regularity that relates directly to stellar parameters. This includes in particular the so-called large and small frequency separations. Extracting these quantities from the oscillation signal allows precise determinations of stellar radii: accuracy of 2 to 3% and ages better than 5% of the total main sequence lifetime.

The Kepler Asteroseismic Investigation (KAI) is based on a Letter of Direction from the Kepler Project to the KAI. This letter describes the data products provided by the Kepler Project for asteroseismic investigation, as well as the obligations of the KAI including that of providing asteroseismic characterization, in particular radii, of planet-hosting stars to the Kepler Project. This agreement will result in a large amount of high-quality time-series data transferred through the Kepler Asteroseismic Science Operations Centre (KASOC), based at the University of Aarhus, to the Kepler Asteroseismic Science Consortium (KASC), which is a large scientific community participating in the Kepler asteroseismic investigation. Before being distributed to the KASC the data will be pre-processed in order to remove any planetary transit signals that may be present in the data.

Throughout the mission, the KASC will be allowed to select targets for both short- and long-cadence observations. In the initial three-month period of the mission, all 512 short-cadence targets will be selected for asteroseismology. This number will decrease as planet candidates are discovered through the long-cadence observations and put on short cadence for better coverage of the transits. However during the entire mission 240 short-cadence targets will continue to be reserved for asteroseismology, of which at least 140 can be selected by KASC.

7. Community Participation and Data Access

The community can participate in the Kepler Mission in several ways: a participating scientist program (PSP), a guest observer (GO) program, and an Astrophysical Data Analysis Program (ADP). The PS program was advertised in 2007 and eight investigations were chosen. The GO is expected to be announced by NASA Headquarters in 2008 followed by the ADP program after data have been received, calibrated, and released.

7.1. *Participating Scientist Program*

The PSP was conceived to solicit proposals from the science community to complement the primary science goals of the Kepler Mission. As described in the NASA ROSES-2007 section D.10, this includes such tasks as the detection of non-transiting planets using timing variations, improvements in determining the size of stars, and performing ground-based observing to aid in elimination of false-positives. Eight investigators were selected for addition to the Kepler science team. Their names and the titles of their investigations are:

- William Welsh, "Detailed Modeling of Extrasolar Planet Transit Observations"
- Derek Buzasi, "Removing A Source of Planetary Detection Bias: Stellar Granulation Models for Kepler"
- Matt Holman, "Applying the Method of Transit Timing Variations to Kepler"
- Jason Steffen, "Detecting Additional Planets in Transiting Systems Using Transit Timing Variations"
- Eric Ford, "Characterizing the Orbital Eccentricities of Earth-like Planets with Kepler"
- Jonathan Fortney, "Giant Planet Science from the Kepler Mission"
- Sara Seager, "Theoretical Interpretation of Kepler Exoplanet Albedos and Reflected Light Curves"
- Laurance Doyle, "Detection of Extrasolar Planets Around Eclipsing Binaries in the Kepler Field"

Welsh's investigation will provide a careful analysis of sets of transits to determine the best possible transit times. Corrections will be made for astrophysical processes such as differential limb darkening with wavelength, durations of immersion and emersion, curved transit paths, and planet oblateness.

Buzasi's study of the effects of non-uniformities of the stellar surface on the determination of the transit timing centroids will complement that of Welsh as well as characterize the spatial variations of the stellar flux and the photometric noise introduced by these variations.

The timing variations derived from these two studies will be used by Steffen and Holman to detect the presence of non transiting planets and to estimate their period and mass. These studies will help describe the planetary systems after transiting planets have been discovered. Unless other planetary systems differ from the Solar System in having many of the orbital planes so well aligned that several planets show transits, transit timing and RV observations of the massive planets will be needed to explore the structure of the planetary systems discovered by Kepler. (See scientific goal *e* in Section 2.)

Eric Ford will be using an analysis of the structure and duration of the primary transits and possible secondary eclipses to estimate the orbital eccentricity of the transiting planets.

Seager and Fortney will work with the Kepler observations of reflected light from both transiting and non-transiting planets with short period orbits. Based on the measured variability of the Sun over periods of days to weeks, it is possible that reflected light signals will be detected from the phase variations as the planet orbits its star.

7.2. *Guest Observer Program*

Within the GO program, scientists may propose to view objects within the Kepler FOV which are not already on the planet detection target list, whether galactic or extragalactic. The Kepler Target Catalog (KTC) is expected to become publicly available shortly before launch. In general one may assume that all F-, G-, and K-dwarf stars to V = 14-15 and M-dwarf stars to V = 16 are already on the observing list and any other object is not.

https://doi.org/10.1017/S1743921308026513 Published online by Cambridge University Press

Proposed objects will typically be observed for a minimum of three months, but could extend as long as the mission duration. Capacity for three thousand objects has been set aside for this program. The data will be processed using the standard Kepler pipeline to produce de-trended light curves. Solicitation for GO proposals is expected prior to launch with observing to begin shortly after commissioning.

7.3. *Astrophysical Data Analysis Program*

There are potentially a host of other astrophysical uses for the Kepler data (Granados & Borucki 1994), given the uniqueness in precision, completeness, duration and number of stars in the archived data. Potential uses include such things as; analysis of white light flaring and stellar activity, which can yield star spot cycles, especially if the mission is extended beyond about half of a solar cycle; the frequency of Maunder minimums for solar-like stars, which has implications for paleoclimatology and perhaps the future of our Earth's climate; cataclysmic variables, providing pre-outburst activity and mass transfer rates; and active galactic nuclei, providing a measure of the "engine" size in BL Lacs, quasars and blazers.

8. Data Release Policy

To avoid publication of false positives, the series of ground-based observations described above must be made and analyzed before any announcements are made. To schedule sufficient time to get telescope time, make the observations with the usual time lost due to bad weather and to the limited seasonal observability of the star field, will require several months. Hence the data will not be released until several months have passed from the time that at least three transits have been detected.

For planets with short orbital periods, three or more transits will be seen within the first months of operation. Release of the data for the announced discoveries is expected by the end of the first year of operation. Shortly thereafter, data and light curves for those stars found to be too variable to be useful targets will also be released. Data for low-amplitude transits with long periods will occur only at the end of the mission. When the data are released, both original calibrated data for each target and the light curves generated by ensemble photometry will be provided so that all interested members of the science community can independently assess the reliability of the results or reprocess the data.

9. Status and Summary

Kepler is NASA's first mission capable of detecting Earth-size and smaller exoplanets in the HZ. The hardware and software are progressing through development toward a launch in February of 2009. The photometer assembly and integration are complete. Testing of the assembly will be complete this fall and the system will be shipped to Cape Kennedy in December 2008. The mission is designed to be capable of detecting hundreds of terrestrial planets, if they are common, or provide a significant null result if they are not. Either result will be profound. Robust programs are in place to validate the discoveries and to involve the science community.

Acknowledgements

Funding for this mission is provided by NASA's Astrophysics Division.

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