The Kepler Mission

*A Transit-Photometry Mission to Discover Terrestrial Planets*

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**Abstract.** The *Kepler* Mission is a NASA Discovery-class mission designed to continuously monitor the brightness of 100,000 main sequence stars to detect the transit of Earth-size and larger planets. It is a wide field of view photometer with a Schmidt-type telescope and an array of 42 CCDs covering the 100 sq. degree field-of-view (FOV). It has a 0.95 m aperture and a 1.4 m primary and is designed to attain a photometric precision of 20 parts per million (ppm) for 12th magnitude solar-like stars for a 6.5-hour transit duration. It will continuously observe 100,000 main sequence stars from 9th to 15th magnitude in the Cygnus constellation for a period of four years with a cadence of 4 measurements per hour. *Kepler* is Discovery Mission #10 and is on schedule for launch in 2007 into heliocentric orbit. A ground-based program to classify all 450,000 stars brighter than 15th magnitude in the FOV and to conduct a detailed examination of a subset of the stars that show planetary companions is also planned. Hundreds of Earth-size planets should be detected if they are common around solar-like stars. Ground-based spectrometric observations of those stars with planetary companions will be made to determine the dependences of the frequency and size of terrestrial planets on stellar characteristics such as type and metallicity. A null result would imply that terrestrial planets are rare.
1. Introduction

Small rocky planets at orbital distances from 0.9 to 1.2 AU are more likely to harbor life than the gas giant planets that are now being discovered with the Doppler-velocity technique. Technology based on transit photometry can find smaller, Earth-like planets that are a factor of several hundred times less massive than Jupiter-like planets. The Kepler Mission is designed to discover hundreds of Earth-size planets in and near the habitable zone (HZ) around a wide variety of stars. Kepler was selected as NASA Discovery Mission #10 in December 2001. A description of the mission and the expected science results are presented.

2. Scientific Goals

The general scientific goal of the Kepler Mission is to explore the structure and diversity of planetary systems with special emphasis on determining the frequency of Earth-size planets in the HZ of solar-like stars. This is achieved by surveying a large sample of stars to:

- Determine the frequency of 0.8 Earth-radii \((R_p)\) and larger planets in or near the habitable zone of a wide variety of spectral types of stars;
- Determine the distributions of sizes and orbital semi-major axes of these planets;
- Estimate the frequency of planets orbiting multiple-star systems;
- Determine the distributions of semi-major axis, eccentricity, albedo, size, mass, and density of short period giant planets;
- Identify additional members of each photometrically-discovered planetary system using complementary techniques; and
- Determine the properties of those stars that harbor planetary systems.

3. Photometer and Spacecraft Description

The instrument is a wide FOV differential photometer with a 100 square degree field of view that continuously and simultaneously monitors the brightness of 100,000 main-sequence stars with sufficient precision to detect transits by Earth-size planets orbiting G2 dwarfs. The brightness range of target stars is from visual magnitude 9 through 15. The photometer is based on a modified Schmidt telescope design that includes field flatteners near the focal plane. Figure 1 is a schematic diagram of the photometer. The corrector has a clear aperture of 0.95 m with a 1.4 m diameter \(F/1\) primary. This aperture is sufficient to reduce the Poisson noise to the level required to obtain a 4\(\sigma\) detection for a single transit from an Earth-size planet transiting a 12\(^{\text{th}}\) magnitude G2 dwarf. The focal plane is composed of forty-two 1024 \(\times\) 2200 backside-illuminated CCDs with 27 \(\mu\)m pixels.
Figure 1. Schematic diagram of Kepler photometer.

Figure 2. Integrated spacecraft and photometer.
The detector focal plane is at prime focus and is cooled by heat pipes that carry the heat out to a radiator in the shadow of the spacecraft. The low-level electronics are placed immediately behind the focal plane. A four-vane spider supports the focal plane and its electronics and contains the power- and signal-cables and the heat pipes.

The spacecraft bus encloses the base of the photometer, supports the solar panels, and provides attachment for power, communication, and navigation equipment. Several antennas with different frequency coverage and gain patterns are available for uplink commanding and for data downlink. A steerable high-gain antenna operating at Ka band is used for high-speed data transfer to the Deep Space Network (DSN). It is the only articulated component other than the ejectable cover. Approximately 1 GByte/day of data are recorded and then transferred to the ground every few days when contact is made with the DSN. The spacecraft provides very stable pointing using four fine guidance sensors mounted in the photometer focal plane. Small thrusters are used to desaturate the momentum wheels. Sufficient expendables are carried to extend the mission to six years.

Both the instrument and the spacecraft are being built by the Ball Aerospace and Technology Corporation (BATC) in Boulder, Colorado. (See Figure 2.)

4. Scientific Approach

To achieve the required photometric precision to find terrestrial-size planets, the photometer and the data analysis system must be designed to detect the very small changes in stellar flux that accompany the transits. In particular, the variability of the star, on time scales different than that of the transits, is not of interest. Sharp images of the star field are not helpful because the PSF must be over-sampled and because a broad image profile reduces the sensitivity to image motion. This provides the best estimates of image centroids that are used to reduce the systematic error due to image drift. The Kepler Mission approach is best described as “differential relative photometry”. In this approach;

- Target stars are always measured relative to the ensemble of similar stars on the same part of the same CCD and read out by the same amplifier.
- Only the time change of the ratio of the target star to the ensemble is of interest. Only decreases from a trend line based on a few times the transit duration are relevant (long-term stability of the trend is not required).
- Target star and ensemble stars are read out every three seconds to avoid drift and saturation
- A broad PSF is used to avoid saturated pixels and to allow image centroids to be tracked and used to reduce systematic errors.
- Correction for systematic errors is critical. See the description in Jenkins et al. (2000).
Photometry is not done on the spacecraft. Instead, all of the pixels associated with each star image are sent to the ground for analysis. This choice allows many different approaches to be used to reduce systematic errors.

The spacecraft is placed in an Earth-trailing heliocentric orbit by a Delta II 2925-10L launch vehicle. The heliocentric orbit provides a benign thermal environment to maintain photometric precision. It also allows continuous viewing of a single FOV for the entire mission without the Sun, Earth or Moon obstructing. Only a single FOV is monitored during the entire mission to avoid missing transits.

A pattern of at least three transits that shows that the orbital period repeats to a precision of at least 10 ppm and that shows at least a $7\sigma$ detection is required to validate any discovery. The mission lifetime of four years allows four transits to be observed so that $8\sigma$ detections can be obtained from Earth-size planets transiting solar-like stars. A detection threshold of $7\sigma$ is required to avoid false positives due to random noise.

Planetary signatures exhibiting mean detection statistics of $7\sigma$ will be recognized 50% of the time. The recognition rate for planets exhibiting $8\sigma$ detection statistics increases to 84%. This increase means that the false negative event rate falls from 50% to 16%. Signal detection algorithms that whiten the stellar noise, fold the data to superimpose multiple transits, and apply matched filters are employed to search for the transit patterns down to the statistical noise limit (Jenkins, 2002). From measurements of the period, change in brightness and known stellar type, the planetary size, the semi-major axis and the characteristic temperature of the planet can be determined.

Only data from pixels illuminated by preselected target stars (i.e., $\sim 20$ pixels/star) are saved for transmission to Earth. Data for each pixel are co-added onboard to produce one brightness measurement per pixel per 15-minute integration.

Data for target stars that are monitored for p-mode analysis are measured at a cadence of once per minute. In the Sun, a series of modes with periods of about 3 minutes and equal in spacing in the frequency domain are excited to a level of about 3 ppm in white light. This level of precision requires the detection of at least $10^{12}$ photons. Kepler provides the necessary photon-electron levels in one month for 3600 dwarf stars brighter than $m_v = 11.4$ in the FOV.

5. Selection of Target Stars and Field of View

Approximately 100,000 target stars must be monitored to get a statistically meaningful estimate of the frequency of terrestrial planets in the HZ of solar-like stars. A FOV centered on a galactic longitude of 70 deg and latitude of + 6 deg satisfies both the constraint of a 55 degree sun-avoidance angle and provides a very rich star field. This FOV falls within the Cygnus constellation and results in looking along the Orion spiral arm (see Figure 3). In the 100 sq degree Kepler FOV, there are...
Figure 3. *Kepler FOV* in the Cygnus constellation, looking along the Orion spiral arm.

approximately 450,000 stars brighter than 15th magnitude. Studies are underway to determine the most efficient way of classifying such a large number of stars and choosing the approximately 100,000 late-F, G, and K dwarfs as targets. The current approach is to use wide FOV ground-based telescopes with a new color-filter system to identify both the luminosity class and spectral types and thereby enable the elimination of giants and early spectral types from the target list.

If 100,000 solar-like stars are monitored and if every such star has a single planet with an orbital semi-major axis of 1 AU, then only about 500 planets can be discovered because the geometrical probability that the planets’ orbit will be aligned well enough to show transits is only about 0.5%.

6. Expected Results

After the mission ends, the results can be summarized as graphs analogous to those shown in Figure 4. Because both the size and mass of the stars that are found to have planets will be determined by follow-up observations, the size of the planets and their orbital semi-major axes can be determined. If most stars have planets approximately the size of the Earth (0.9 < R⊕ < 1.2), for example, then we should find data points along the curve marked “Earth-size”. At distances near 1 AU (0.8 < a < 1.2 AU), we expect approximately 25 planets. If most stars have two such planets (like Earth and Venus) in that region, then there will be a point showing that 50 planets were detected there. If stars often have planets 30% larger, then because such planets are more readily detected, points along the curve marked “1.3 R⊕” will be recorded and a data point for 200 planets will be plotted for a semi-major axis near 1 AU. Planets twice the radius of the Earth (i.e.,
Figure 4. Trace of the number of planets expected to be detected if all stars have one planet at the position indicated. Note the high sensitivity of the results to the planet diameter and the orbital semi-major axis.

Approximately 10 times the mass of the Earth) are readily detected even for large or dim stars so about 600 planets should be detected near 1 AU.

These values are based upon a realistic distribution of spectral types for a magnitude-limited survey. For a limiting visual magnitude of 14, about 50% of the stars will be early types that are too big to produce a SNR $> 7$ for an Earth-size planet and/or too massive to produce a pattern with at least three transits during the four-year mission duration. Studies are underway to find somewhat dimmer stars of later spectral type that would have sufficiently large signals to overcome the increased photon shot noise. If there is an efficient way to find such stars, they will replace many of the brighter-but-earlier-spectral-type stars. This change could nearly double the number of small planets found with large values of semi-major axes.

As the semi-major axis decreases, the expected number of discoveries rises very rapidly, even on a log plot. This occurs for two reasons. First, the probability of a detection increases as the inverse of the orbital radius and second, the number of transits that occur during the mission lifetime increases. The detectability of transit patterns rapidly increase with the signal-to-noise ratio (SNR) and the SNR increases with the square root of the number of transits. At the value of the semi-major axis found for the “hot Jupiters” detected by the Doppler velocity technique, i.e., $\sim 0.05$ AU, tens of thousands of planets should be found if they are common orbiting solar-like stars. Even if the planets are as small as Mars or Mercury, the number of transits that occur in such tight orbits during a four year mission will be so large ($\sim 400$) that small planets should be found in profusion.

Of course, there is no reason to expect that all solar-like stars have planets and therefore the actual data points are likely to fall well below the curves shown in
Nevertheless, if planetary frequencies are as high as 1%, many terrestrial-size planets should be found.

After two years of operation, the *Kepler* Mission should provide a good estimate of the frequency of Earth-size planets with orbital periods as long as six months. Once the mission length reaches four years, a good estimate of that frequency will be obtained for planets in the HZ of solar-like stars. However, because not all stars are expected to have Earth-size planets in the HZ, and because the HZ could extend to the orbit of Mars (Kasting et al., 1993; Franck et al., 2000), it is worth considering the benefit of an extension of the mission from the planned four years to six years. The uppermost curves in Figure 5 show the dependence of the expected number of discoveries of Earth-size planets on the mission duration and semi-major axis. Clearly, the fractional increase in planet discoveries is dramatic for semi-major axes of 1 AU and larger. The increased mission duration raises the number of expected detections by a factor of two at 1 AU and a factor of 3.5 at 2 AU. If Earth-size planets are rare, this increase could be very helpful in providing an estimate of the number of stars that must be observed by the Darwin/TPF mission if it is to fulfill its goal of determining the atmospheric composition of Earth-size planets in the HZ of solar-like stars.

Planets as small as Mars might be habitable if they are well placed in the HZ. Such planets can be detected if the stars are smaller than the Sun or if the planets are in short period orbits. K stars are smaller and cooler than the Sun and have their HZ at distances of 0.2 to 1.0 AU. Hence the orbital periods in the HZ are measured in months and the total SNR of Mars-size planets is sufficient for valid detections. Again note the dramatic increase in the discovery result as the mission duration increases. At a semi-major axis of 0.5 AU, no planets are expected if the mission duration is 3 years. Two are expected for a 4-year mission and six are expected when the mission duration is increased to six years. It is clear from the lower curves, that knowledge of the lower end of the size distribution of rocky planets will be significantly improved by increasing the mission duration to six years.

Giant planets, like 51 Pegasi, with orbits of less than seven days are also detected by the periodic phase modulation of their reflected light without requiring a transit (Borucki et al., 1997; Hatzies, 2003). For the short-period giant planets that do transit, the planetary albedo can be calculated. Information on the scattering properties of the planet’s atmosphere can also be derived (Marley et al., 1999; Sudarsky et al., 2000; Seager et al., 2000).

Ground-based Doppler spectroscopy and/or space-based astrometry with SIM can be used to measure the planetary masses, if they are jovian or larger, and to distinguish between a planet and a brown dwarf. These complementary methods can also detect additional massive companions in the systems to better define the structure of each planetary system. The density of any giant planet detected by both photometry and either of the other methods can be calculated.
Thus, the results from this mission will allow us to place our solar system within the spectrum of planetary systems in our Galaxy and develop theories based on empirical data by providing a statistically robust census of the sizes and orbital periods of terrestrial and larger planets orbiting a wide variety of spectral types.

White dwarf stars are about the size of the Earth and might be expected to produce a transit signal of similar magnitude. However, because of the gravitational lensing caused by their large-but-compact mass, the transits actually result in an increase in brightness (Sahu and Gilliland, 2003) and are thereby readily distinguished from those of a planet.

### 7. Influence of Stellar Variability on the Detectability of Transit Signals

Stellar variability sets the limit to the minimum size of planet that can be detected. It reduces the signal detectability in two important ways:

- The variability introduces noise into the detection passband and thereby reduces the signal to noise ratio (SNR) and thus the statistical significance of transits.
- Because the flux of every target star is ratioed to the fluxes of many surrounding stars to reject common-mode instrument noise, variability of the stars used in the normalization introduces noise into the target star signal.
The second concern can be alleviated by measuring the variability of each star relative to an ensemble of others and then iteratively removing the noisiest from the list of comparison standards. To mitigate the effects of the first concern, stars must be chosen that have low variability. Power spectra for the Sun at solar maximum and minimum are shown in Figure 6.

Also shown are the energy spectra for transits with 8- and 10-hour durations. It’s clear that most of the solar variability is at periods substantially longer than those associated with planetary transits. In particular, the Sun’s variability for samples with duration similar to that for transits is about 10 ppm. For stars rotating more rapidly than the Sun, the power spectrum will increase in amplitude and move to shorter periods thus increasing the noise in the detection passband.

Stellar variability in late-type main sequence stars is usually associated with the interplay of the convective layer and the internal magnetic field. Because the depth of the convective layer is a function of the spectral class of the star and because the activity level is higher when the star is rotating rapidly, the variability of solar-like main sequence stars is related to both their spectral class and rotation rate. Further, because the rotation rate decreases with age, the age of a star is an important variable. Thus we expect that the factors that influence the variability of target stars are age and spectral type.

The age and rotation rate of the Sun are approximately 5 Gyr and 27 days, respectively. The age of the galaxy is about 12 Gyr and about 2/3 of the stars are older than the Sun and are expected to be at least as quiet as the Sun. That extrapolation cannot be verified by examining the actual photometric variability.
of solar-like stars because no star other than the Sun has been measured to the requisite precision. However, the $R'_{HK}$ index is believed to be well correlated to stellar variability. It is based on the spectral line profile of the Calcium H and K lines and is readily measured with ground-based telescopes. Figure 7 shows measurements of the $R'_{HK}$ index for a variety of spectral types. Observations show that about 70% of the stars are found to have the index at least as low as that of the Sun which strengthens the argument that most solar-like stars will be at least as quiet as the Sun. Hence we plan to choose approximately 130,000 late type dwarfs to monitor during the first year of observations and then gradually eliminate those that are too variable to find Earth-size planets. This is necessary because the telemetry rate will decrease as the spacecraft recedes from the Earth.

Although most solar-like stars are expected to have low stellar activity levels, planets can still be found around stars with higher activity levels if the size of the planets are somewhat larger than the Earth or if they are found in the habitable zone of later spectral types. Planets in the HZ of K dwarfs have orbital periods of a few months and therefore would show about 16 transits during a four-year mission. Figure 7 shows the minimum size planet required to produce an $8\sigma$ detection versus the amplitude of the stellar variability assuming that the frequency distribution of the stellar noise is the same as that of the Sun. The upper curve shows that the amplitude of the stellar noise would need to be at least eight times that of the Sun before it would prevent planets slightly larger than twice the radius of the Earth from being detected. For planets showing 16 transits, planets as small as 1.4 times the radius of the Earth would still be detectable.
Table I. Comparison of Signal and Noise and Minimum Size Planet that Produces an 8σ Signal

<table>
<thead>
<tr>
<th>Visual magnitude</th>
<th>9</th>
<th>12</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stellar signal (photo electrons)</td>
<td>$9 \times 10^{10}$</td>
<td>$6 \times 10^{09}$</td>
<td>$9 \times 10^{08}$</td>
</tr>
<tr>
<td>Stellar shot noise (ppm)</td>
<td>3.3</td>
<td>13</td>
<td>35</td>
</tr>
<tr>
<td>Instrument noise (ppm)</td>
<td>1.7</td>
<td>7</td>
<td>30</td>
</tr>
<tr>
<td>Solar variability (ppm)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Relative signal for Earth transit across the Sun (ppm)</td>
<td>84</td>
<td>84</td>
<td>84</td>
</tr>
<tr>
<td>SNR for 4 transits</td>
<td>15</td>
<td>9</td>
<td>3.5</td>
</tr>
<tr>
<td>Minimum detectable planet radius (Earth=1) at 8σ</td>
<td>0.5</td>
<td>0.9</td>
<td>2.3</td>
</tr>
</tbody>
</table>

8. Comparative Importance of Various Sources of Noise

As described earlier, it is important to find planets with a size sufficient to produce 8σ detections with three or more transits. Equation 1 shows the relationship (greatly simplified) to the signal to noise ratio (SNR) as a function of ratio of the area of the planet to area of the star ($A_p/A_*$), number of transits ($N_{tran}$), and the noise due to stellar variability ($v$), Poisson noise in the stellar flux ($F$), and instrument noise ($i$);

$$SNR = (N_{tran})^{1/2}(A_p/A_*)/[(i^2 + v^2) + 1/F]^{1/2}$$

An examination of this equation shows that for very bright stars where $1/F$ is small and when the stellar variability dominates the instrument noise, the SNR is dominated by the stellar variability. The opposite is true for dim stars where $1/F$ is large and the SNR is dominated by the shot noise in the stellar flux. Table I presents calculated noise values for Kepler instrument. For all entries in this table, a stellar variability of 10 ppm is assumed. Note that at 14th magnitude, that although the effect of stellar variability is negligible, instrument noise also makes a substantial contribution. Such large values of instrument noise warn that assuming shot-noise-limited performance is unwarranted. It is also clear that for stars 14th magnitude and dimmer, detectable planets must be somewhat larger than the diameter of the Earth if they are to be reliably detected orbiting G2 dwarfs.

9. Validation of Planet Detections

Before a candidate detection can be considered to be a validated planet and the information released to the public, a rigorous validation process must be executed to ensure that it is not due to some other phenomenon (Jenkins et al., 2002). Public release of false positives would ultimately discredit any mission results. There-
fore to be considered a reliable detection the candidate planet detection must meet several requirements.

- The total SNR of the superimposed transits must exceed $7\sigma$. This requirement prevents false positives produced by statistical noise when $8 \times 10^{11}$ statistical tests are carried out on $10^5$ stars for orbital periods from 1 to 700 days.
- At least three transits must be observed that demonstrate a period constant to 10 ppm. This test is independent of the previous test and demonstrates the presence of a highly periodic process. It essentially rules out mistaking stellar phenomenon for transits.
- The duration, depth, and shape of the light curve must be consistent. The duration must be consistent with Kepler’s laws based on the orbital period. The depth must be consistent over all transits. A weaker requirement is that the shape must be consistent with a “U” shape of a planetary transit rather than a “V” shape of a grazing eclipse of a binary star. Clearly, low-amplitude transits are likely to be too noisy to make this distinction.
- The position of the centroid of the target star determined outside of the transits must be the same as that of the differential transit signal. If there is a significant change in position, the cause of the signal is likely to be an eclipsing star in the background.
- Radial velocity measurements must be conducted to demonstrate that the target star is not a grazing eclipsing binary.
- High precision radial velocity measurements must be made to measure the mass of the companion or provide an upper limit that is consistent with that of a small planet.
- High spatial resolution measurements must be made of the area immediately surrounding the target star to demonstrate that there is no background star in the aperture capable of producing a false positive signal.

It is also possible that future instrumentation on HST and JWST will have sufficient precision to detect the color changes during the transit. A measured color change consistent with the differential limb darkening expected of the target star (Borucki and Summers, 1984) would strengthen the validation. A shape or depth substantially different than expected would point to the possibility of a very close background star that differed in spectral type.

10. Mission Status

The Kepler Mission was chosen as Discovery Mission #10 in December of 2001 and funds to proceed were received to start the Phase B work in early 2002. An outline of the mission schedule is shown in Figure 8. Detectors and the optical components have been ordered. In the summer of 2002, a new management team from the Jet Propulsion Lab was chosen to provide overall mission management.
The JPL team members have been smoothly integrated with those at Ames and BATC. Their addition greatly strengthens the Kepler Mission by providing great depth in mission management and engineering.

In summary, the Kepler Mission is on schedule for an October 2007 launch.

References


